CHARACTERIZATION OF BEHAVIOUR OF THE POLYMERIC SEAL USING FINITE ELEMENT METHOD

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MAY, 2003

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A Thesis Submitted
in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF TECHNOLOGY

May 2003

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CERTIFICATE

It is certified that the work contained in the thesis entitled **"Characterization of Behaviour of the Polymeric Seal Using Finite Element Method** by *Mukesh Rawat* has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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May, 2003

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude and thanks to my thesis supervisor Dr. Kamal K Kar for his guidance, invaluable suggestions and constant encouragement. I am also grateful to him for exposing me to the practical aspects vibration diagnostics I am also thankful to Dr. Singh, DMSRDE Kanpur, and Mr Sinha, IGCAR Kalpakkam for their valuable suggestions.

I am thankful to Siva Prashad and Rajkumar, for their invaluable help and tips with ABAQUS, G. Saravana Kumar, T V.K.Gupta, M.L.Jain, M Shukla, Dharmendra, Sulakhe, for helping me in all possible ways, Yuandhar, Vaibhav and Surya for the lively work environment they have provided.

I appreciate and extend my sincere thanks to A. Chatterji (Coordinator CAD lab) for his untiring help in sorting out software problems. I thank all those who have contributed directly or indirectly to my thesis.

Indian Institute of Technology, Kanpur. Mukesh Rawat

May 2003

ABSTRACT

Finite element analysis of polymeric seal at medium strain (strain less than 100%) is carried out under static and dynamic conditions to optimize the dimension of seal. The stress strain behaviour of a black filled ethylene propylene (EPDM) polymer and fluorocarbon (FKM) used to manufacture polymeric seal, has been studied in extension over a range of temperature to examine the validity of Arruda-Boyce, Moony-Rivlin, Neo-Hooken, Ogden, Polynomial, Reduced polynomial, Van der Waals and Yeoh models. The analytical form of strain energy density function for Arruda-Boyce model gives a very good fit to the experimental data for strain less than 100%, which cover the range of interest for most engineering applications. The material constants for above known nonlinear elastic constitutive theories, which are be used directly with the finite element analysis, are also evaluated. Axisymmetric analyses are performed both for unbeaded and beaded seals to optimize the dimension of seals.

KEY WORDS: Polymeric seal, Unbeaded seal, Beaded seal, Strain energy density function, Ethylene propylene polymer, fluorocarbon, Arruda-Boyce

NOMENCLATURE

C_{ij}	Rivlin coefficients
D_i	Material incompressibility
R_t	Volumetric expansion with change in temperature
U	Strain energy density function
C_{10}, C_{01}	Mooney-Rivlin material constants
J	Total volume ratio
J_{el}	Elastic volume ratio
λ_i	Principle stretch
μ_0	Initial shear modulus
K_0	Bulk modulus
$\bar{I}_1$, $\bar{I}_2$	First deviatoric strain invariant
λ_m	Locking stretch
a	Global interaction parameter
β	Invariant mixture parameter
N	Material parameter
α_i	Temperature-dependent material parameters

CONTENTS

CHAPTER 1

INTRODUCTION

Seals are critical components in virtually all mechanical devices which are used for closing the gap and also to separate two liquids or gasses in static or dynamic applications. There are various types of seals like, compression packing seals, dynamic seals, exclusion seals, hydraulic and pneumatic seals, O-ring Inflatable seals, gasket, Inflatable seals, etc. Devices containing single/hundred of seals are common and the failure of a single seal often has catastrophic consequences. Accordingly, tremendous effort has gone into improving seal design. Despite this effort, progress has been slow and seals today appear, for the most part, identical to seals used thirty years ago. Nonetheless, there has been significant progress in seal technology in terms of both operational life and sealing characteristics. Much of this improvement has been the result of empirical, trial-and-error engineering. The complexity of seals and the difficulties associated with resolving essential parameters, both material and geometric, have hindered the effectiveness of experimental and theoretical approaches to seal design. There have, however, been a number of significant fundamental studies that have improved the understanding of seals and of how they fail.

1.1: Different Types of Seal

Compression packing seals or gland seals include compression packing, gaskets, mechanical seals, gasket material and other fluid sealing devices Sealing is accomplished by tightening the gland, so that the packing is compressed onto the surface to be sealed. This is a broad category covering seals that are manufactured in a wide array of shapes, sizes, and constructions from many materials.

Dynamic seals include oil seals, hydraulic and pneumatic seals, exclusion seals, labyrinth seals, piston rings, and bearing isolators. Dynamic seals are

used to create a barrier between a rotating and a stationary surface. They function to retain or separate lubricants or fluids, keep out contamination, and contain pressure. For proper installation, the seal lip should point towards the medium being contained. When selecting compression packing materials, it is important to understand a number of specific parameters that can affect performance. the size of the cross section that must be sealed, the media and its specific qualities, the type of equipment (i.e., pumps, valves, mixers, etc), the temperature and pressure of the media being sealed, and shaft or rubbing speed if the machinery is a pump or rotates.

Exclusion seals are primarily used to keep dirt and other contaminants from passing into bearings and other sensitive areas. Some of the device that fall within the exclusion seals category does not actually have any sealing capabilities. Instead, they serve to wipe or scrape away debris from moving or reciprocating shafts or rods. This helps to protect the seal and extend its life. Exclusion seals are available in three main configurations, V-ring, wipers, and scrapers.

Hydraulic and pneumatic seals include piston seals, rod seals, U-cups, V-cup, and flange packing Hydraulic seals are designed for the reciprocating motion that is common in hydraulic and pneumatic applications, such as cylinders.

O-ring is a solid-rubber seal shaped like a doughnut. When pressed between two mating surfaces, an O-ring blocks the passage of liquids or gases. An O-ring can form a static or dynamic seal. A static seal where the O-ring does not move and is used simply for containing pressure or maintaining a vacuum. Dynamic seals can be reciprocating (like a piston and cylinder), or rotating (shaft rotating in a housing).

Gaskets are used to prevent fluid or gas leaks by providing a barrier between two mating surfaces. The gasket must be able to maintain a seal under pressure and temperature changes. A number of different gaskets are available: pre-cut compression (flat or extruded style), formed-in-place, and cured-in-place

Some gaskets can also be used to shield against electromagnetic and radio frequency interference (EMI/RFI).

Inflatable rubber seals are used in various applications like, clean rooms - by pressurizing the door seal, a positive or negative pressure can be maintained in the room, fluid tight - the seals are used to eliminate leakage where there is a pressurized fluid inside the machinery such as washing machines and paint sprayers and large doors - tolerances are hard to maintain in large opening. The gap created can be taken up by the inflation of the seal. Its Industrial applications range is from medical applications to nuclear power plant operations. Inflatable seals work by introduction of an inflation pressure into the cavity of the inflatable seal. This inflation pressure causes the displacement of the seal affecting a positive seal between the seal and the surface to be sealed. Once the seal inflation pressure is removed the seal returns to its uninflated position. Regulated air is the commonly utilized inflation medium while in some applications pnuematic (gas) or hydraulic (liquid) methods are suitable. Inflatable seals offer versatile configurations in three different planes: radially in, radially out, and axially.

Inflatable seals are homogeneous elastomeric seals with a high modulus of elasticity and considerable tensile strength. The seals are designed to be fitted into grooves and are restricted to low pressures to prevent bursting. They expand and retract with the pressurization and deflation of the seal within a groove. The exact groove and gap dimensions are critical in designing and producing the correct seal for your application. Inflatable high-pressure seals must be captive in slots or grooves within the specified dimensions. Never pressurize or inflate a seal when any one face of the groove is open. Inflatable low-pressure seals are secured by their base and work freely outside the confines of a groove. However, the maximum pressure cannot be applied until their contact face (grooved/toothed side) is against the item to be sealed

1.2: Analysis of Seal:

An extensive literature survey carried out to understand the behaviour of polymer, constitutive theories used for polymeric seal, and finite element methods applicable in this area of research.

A numerical theory of elasticity based on elastic-strain-energy considerations has been developed, mainly by Rivlin[1], for the large strain behaviour of polymeric materials Based on this theory, theoretical relations between stress and strain has been derived from stored energy function for the homogeneous deformation of flat sheets in simple extension, pure shear and two dimensional extension by Treloar[1]. The strain over which these relations applied are typically hundred percent tensile. Strains of this magnitude are considerably higher than those to which conventional classical theory to describe the behaviour of polymer at low strain can be applied.

Key[2] has presented a specialized form Ressner's principle and is suitable mainly for anisotropy incompressible and nearly incompressible materials. Thermoelasticity and finite element method are used to find solutions. This is closely related to the Helinger-Reissner's principle. In these formulations, the descretisation of the hydrostatic stresses is very important and can lead to complete or an average incompressibility of the finite element In the first case, monotonic convergence of the deformation energy is obtained while this property is lost in the second stage case.

A finite element programme for analysis of stretch sheets has been developed by Lindley[1]. The sheet is analyzed using triangular elements assuming homogeneous deformation. The size of the element is chosen to be small over the area where the stress and strain change rapidly, and large where the stress and strain are relatively uniform. The strains and energy within each element are determined form the deformations of the nodal points. Boundary based on displacements rather than forces are consistent with energy approach because the energy function used for polymer is expressed in strains not stresses. A search procedure is followed to find out the position of a nodal point

that minimizes total energy of the sheet, the other nodal points remaining fixed. All points are adjusted in turn until there are no further nodal-point movements

Fried[3] has introduced incompressibility by way of bulk modulus into the finite element with mesh refinement in such a way as to balance it with the residual descretisation energy in order to ensure faster convergence to the incompressible solution. But it is of a purely algebraic nature and large bulk modulus employed in the formulation can cause ill-conditioned stiffness equation or an overly stiff solution.

A finite element method using quadrilateral elements for plane-strain cases and various methods for reducing computations have been proposed by Lindley[1]. A strain-energy function is proposed, which would enable solutions to be obtained at strains well beyond linear classical elasticity theory. However the validity of the method at high-strains cannot be checked by experiments.

Takao[1] has presented symmetric stiffness matrix for incompressible hyper-elastic materials, which gives a better solution than unsymmetrical structure matrices previously used. Thomas and Pain[4] have employed a Resinner type variational principle to formulate mixed finite element for a finite-strain energy analysis of Mooney-Rivlin[1] rubber like materials, by adapting an incremental and stationary lagrangegian formulation. Cescotto and Fonder[5] have proposed a formulation for incompressible materials which is an extension of Hellinger- Resiner's variational principle in the fully plastic range to the domain of non-linear elasticity for materials undergoing large strains. This approach can be interpreted as a penalty method but requires a choice of suitable value of penalty parameter

Batra[6] has also developed a finite element method capable of solving plane strain problems for incompressible elastic materials involving complex geometries and loading conditions. The principle of stationary potential energy is used. Here, the rate of convergence is very slow. Finite elements with penalties in nonlinear elasticity are described by Malkus[7] to enforce the constraints of incompressibility. The tangent stiffness matrix is indefinite when the mesh is

refined and a theoretical analysis of the associated mixed method and a new theorem are seem to lead to a way to retain positive definiteness. This method relies on huge, machine dependent, bulk modulus and reduced integration.

The multiple solutions and related stability problems of polymer elasticity have been studied by Farhad[8]. In case of a simple plane stress problem, it is shown that finite element formulations lead to unstable solutions, among the multiple solutions, when the load exceeds a certain level. A stable solution has been obtained by a simple perturbation method. In general, it has been stated that proper algorithms should be developed in finite element codes, which can detect the stability of the solution and can provide stable solutions.

Weissman[9] has presented a systematic development of mixed finite element models and constructed assumed stress and strain field to avoid locking Formulations for four-node plane strain have been presented by him. Using the model of LaGrange multipliers constraints to functional are added The model can handle only two-dimensional problems The locking behaviour in problems involving internal constraints are discussed and a few simple methods to overcome this difficulty are proposed.

A new approach for the analysis of rubber-like material behaviour is given by Gadala[10] by extending the linear analysis bubble function concept into non-linear analysis. A unified numerical treatment for various constitutive relations of hyperelastic materials is discussed. It has been shown that most of the hyperelastic constitutive relations may be caste into a general form for stress and constitutive matrix calculations. To eliminate external or residual forces on the bubble function or node less degree of freedom, two iterative methods are discussed. However the bubble function had to be condensed and recovered each iteration. Also node less degrees of freedom is not to be associated with any external or residual forces. Hence convergence for this new approach is not sufficient.

Hirabayashi, et al.[11] have optimized the seals used in the cooling system of automobiles after studying how salt used in the anti-freeze crystallized and

damaged the seal. Later, Golubiev and Gordeev[12] have improved the seal design of water pumps operating in fluids with high concentrations of abrasive particles Campion et al.[13] have designed a dynamic seal test facility which functions at up to 100MPa and 250°C to examine a variety of seal systems under various conditions However, the properties of elastomer O-ring seals (Viton, silicone rubber, EPDM) at low temperature have been investigated through the measurement of gas leakage rate and sealing force during thermal cycling between -70 and 20°C by Weise[14]. Ho et el.[15] and Raparelli et al.[16] have developed a software to predict the life of seal over a range of operating conditions, seal materials, seal types and fluids. Sekhar has analysed elastomeric seal used for nuclear reactor using ANSYS software.

1.3: Need for the Present Investigation

To understand the mechanical behaviour of polymeric seals and to improve its life, it is essential to develop a finite element formulation for polymer-like materials and analyse through finite element analysis.

The failure of the seal may be due to the rupture of the seal, leakage across the seal beyond the design leakage value or any damage to the seals, which leads to higher resistance to plug rotation. The main types of loads that are acting on the seal are inflatable pressure, contact stress and tangential load due to the friction under dynamic condition. Since the polymer is continuously nonlinear and also undergoes large deformations, both material and geometric non-linearties should be accounted. Therefore emphasis has to be given to evaluate the stress and strain accurately using nonlinear finite element analysis.

The selection of element for finite element formulation should be simple and also it must be accurate. Hence the polymer can be considered as a Hyperelastic material, Hyperelastic element with sufficient degrees of freedom will be suitable. For establishing contact, elements representing correct contact pair should based on the type of contact establishing either it is 2-D or 3-D. The

loads and boundary conditions should be near to the real conditions. In the light of the above, the scope of the present work has been presented below

1.4: Objective of the Present Investigation

1) To analyse the seal with different geometries under static and dynamic conditions
2) To find out the dimensions of seals which will withstand the specified loading conditions
3) To analyse the seals considering friction under dynamic condition
4) To find out the stresses developed in the seal groove and gap between the seal groove and seal for withstanding the specified loading conditions.

1.5: Problem Definition

Design Requirements of the seals

The seal has to be designed to perform continuously i.e. the seal is engaged all the time without failure for a minimum period of 10 years life under the following conditions.

1. The sealing condition should be maintained properly both in static and dynamic conditions
2. The design pressure is 10 kPa during static/normal and 1 kPa during dynamic condition (The condition is specified by industry)
3. The normal operation temperature is 50^0C.
4. The seal movement during dynamic condition is intermittent rotation in clockwise and anti-clockwise directions (Max. range 180^0C clockwise to 180^0C anti-clockwise).
5. The sealing inflation gas is air

6. The seal shall be sized to withstand a maximum inflation pressure of 250 kPa. However, the seal should provide the desired leak tightness under inflation pressure of 45 KPa during normal operation and 20 KPa during dynamic conditions
7. The seal shall be designed to withstand maximum starting drag and running drag of 600 N/m and 120 N/m length of seal respectively. Maximum number of occurrences of starting drag during design life can be taken as 20
8. The allowable leakage across the seal is 0.0042 cc/s/m length of seal during normal operation and 0.028 cc/s/m length of seal during dynamic handling specified by industries.
9. Allowable permeation leakage is 0.000001 cc/s/m (inflation gas: air inflation pressure 45 kPa at a temperature of 80^{0}C.
10. The maximum stress developed under operating condition should be less than 50% of the tensile strength of polymer.

Groove dimension:

The dimensions of groove are chosen arbitrarily and shown in Figure 1.1 These dimensions are fixed. A seal dimension has to be decided based on the groove dimension

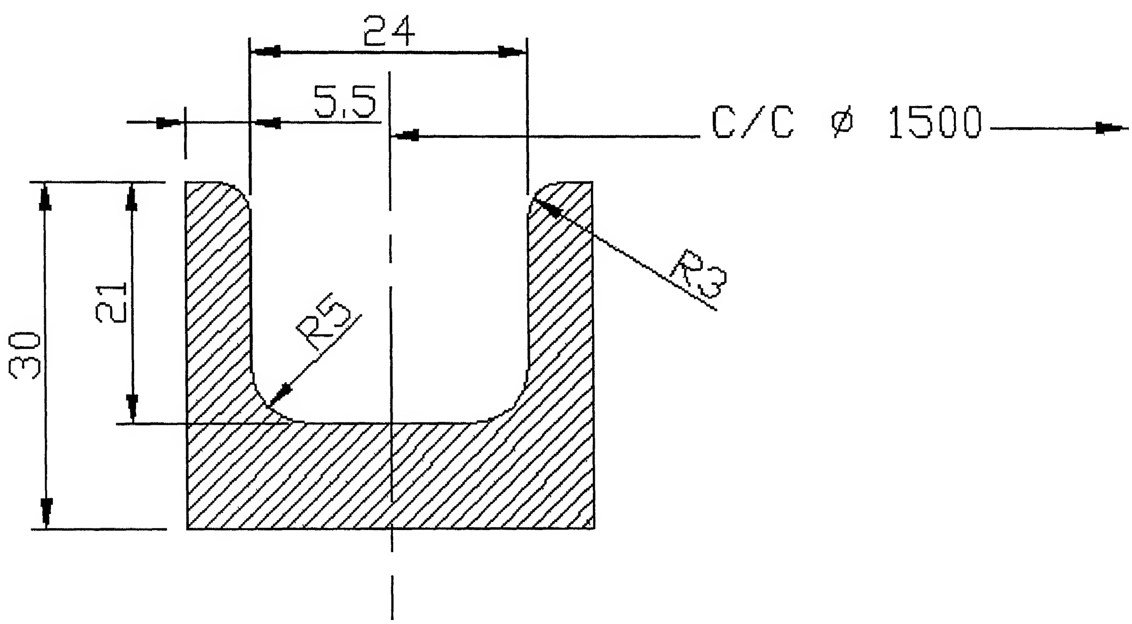


Figure 1 1: Groove dimension chosen arbitrarily.

Seal dimension:

Seal dımensıons are chosen arbitrarıly based on the groove dimension. Two types of seal are used here. These are known as unbeaded seal and beaded seal These are shown in Figures 1.2 and 1.3

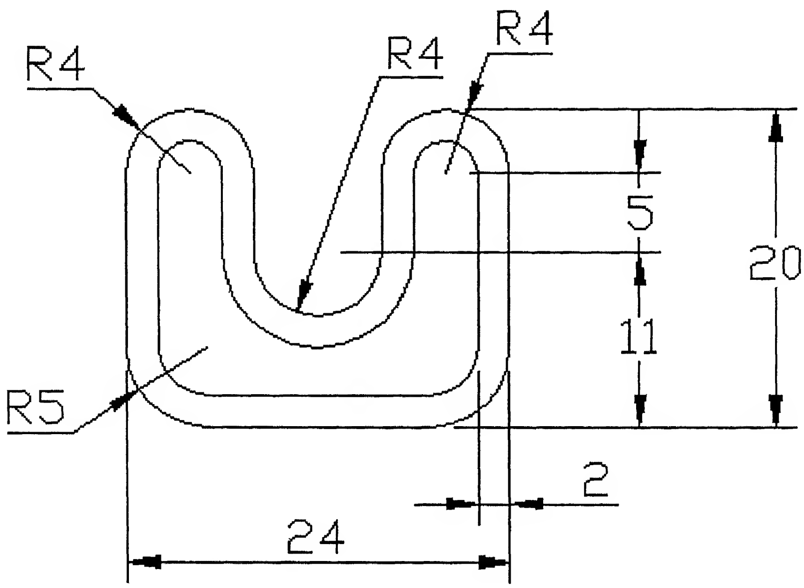


Fıgure 1 2: Dimensions of unbeaded seal

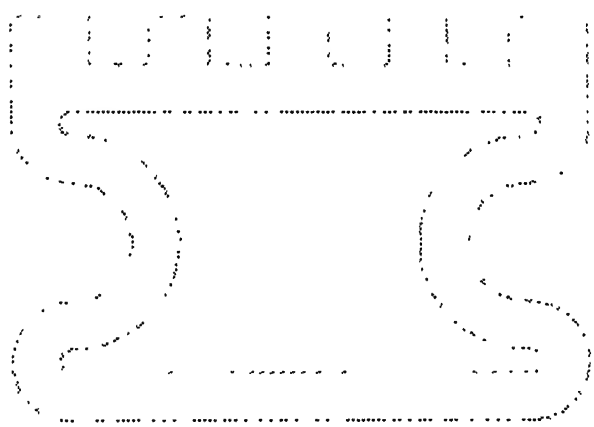


Fıgure 1.3: Geometry of beaded seal

Behaviour of seal under operating condition:

The behaviour of seal under operating condition should be lıke Fıgures 1 4 and 1 5

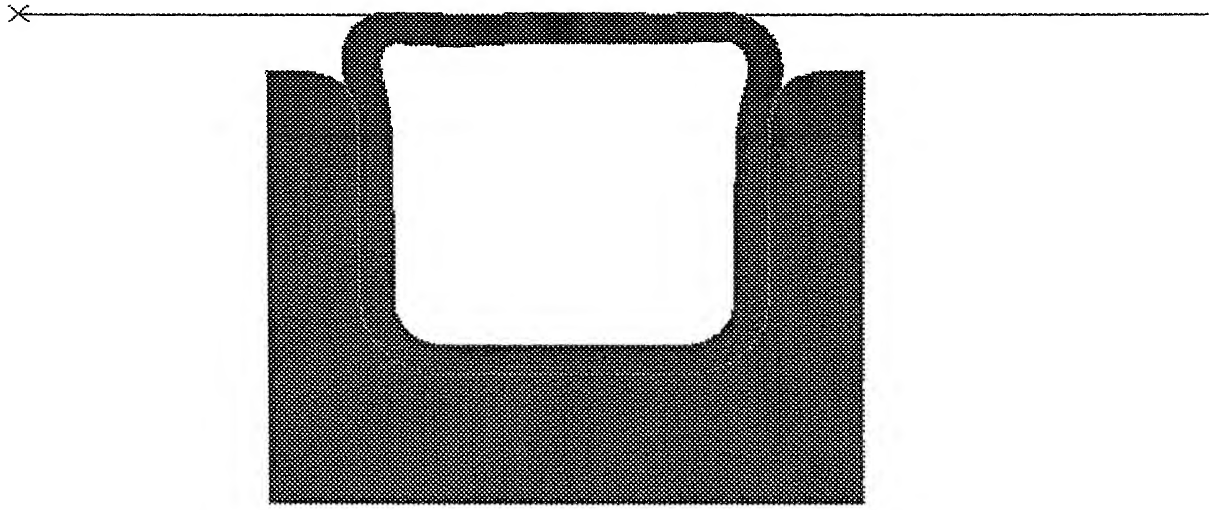


Fıgure 1.4: Ideal behaviour of unbeaded seal under operating condition

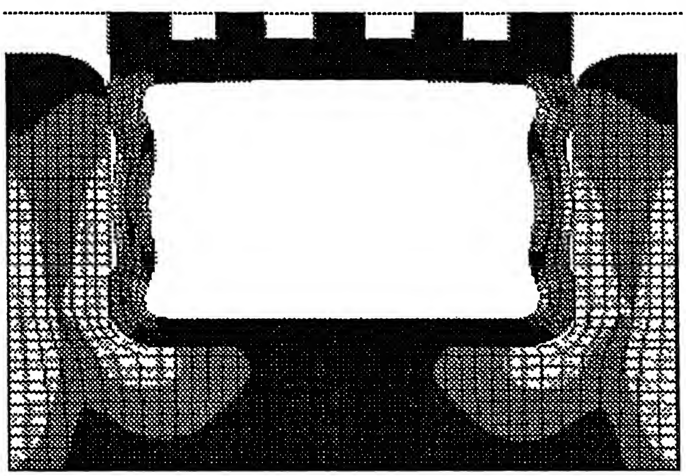


Fıgure 1 4. Ideal behaviour of beaded seal under operating condition

Objective: To find out the optimum dimensions of seal (both unbeaded and beaded seals)

CHAPTER 2

FINITE ELEMENT ANALYSIS

The description and general procedures followed for solving problems using finite element analysis are described here.

2.1: INTRODUCTION

Polymer is recognized as an engineering material because of its unique properties like elasticity and resilience. However, unlike metals, which require relatively few properties to characterize their behaviour, the behaviour of polymer is more complex. It is nonlinear in terms of both material and geometric behaviour Its mechanical behaviour is further complicated by much greater sensitivity to the effects of temperature, environment, strain history, loading rate strain, manufacturing and composition of materials etc

Attempts to characterize the mechanical behaviour of polymer falls into two categories[1]. These are statistical thermodynamics and the phenomenological approach. The statistical thermodynamics approach based on the observations of the elastic force arises that almost entirely from the decrease of entropy with an increase in extension, which follows from the structure of un-stretched polymer being highly amorphous and hence of high entropy. This approach has generally dealt with assumed statistical distribution of lengths, orientations and structure of molecular networks of polymer chain.

But the majority of research work is focused the developments of phenomenological approach based on the observation of polymer under various conditions of homogeneous strain. The phenomenological approach assumes polymer to be an isotropic material in its un-strained state, i.e., the long chain molecules of the polymer are assumed to be randomly oriented Stretching of polymer causes orientation of isotropy can be said to remain valid. This

assumption of isotropy is fundamental to the characterization of polymer by a quantity known as the elastic strain energy functions (W) have been proposed, and these can be sub divided according to whether W is expressed as a polynomial functions of a strain invariants are directly in terms of the principle stretch ratios and whether incompressibility is assumed or not.

Many forms of strain energy density functions are available in the literature and a few widely used are listed below[1].

a) Mooney-Rivlin
b) Arruda–Boyce
c) Neo-Hooken
d) Ogden
e) Polynomial
f) Reduced polynomial
g) Van Der Waals
h) Yeoh
i) Blatz-Ko
j) Peng-Landel
k) Valanis and Landel

a) Mooney-Rivlin: The form of Mooney-Rivlin strain energy potential form is

$$U = \sum_{i+j=1}^{N} C_{ij}(I_1^c - 3)^i (I_2^c - 3)^j + \sum_{i}^{N} \frac{(J^c - 1 - R_t)}{D_i} \qquad \text{....(2.1)}$$

where, C_{ij} = Rivlin coefficients,

D_i = Material incompressibility,

R_t = Volumetric expansion with change in temperature,

$$I_1^c = (\lambda_1{}^c)^2 + (\lambda_2{}^c)^2 + (\lambda_3{}^c)^2 \qquad \text{....(2.2)}$$

$$I_1^c = (\lambda_1{}^c\ \lambda_2{}^c)^2 + (\lambda_2{}^c\ \lambda_3{}^c)^2 + (\lambda_3{}^c\ \lambda_1{}^c)^2 \qquad \text{....(2.3)}$$

$$J^c = \lambda_1{}^c\ \lambda_2{}^c\ \lambda_3{}^c \qquad \text{....(2.4)}$$

$$\lambda_i{}^c = \frac{\lambda_i}{(J^c)^{1/3}} \qquad \text{....(2.5)}$$

The first series in Eqn. (2.1) represents the deviatoric component of stored energy density, being the contribution that can be associated with shearing type deformations alone Coefficients C_{ij} are found regression of the chosen expansion of the first series to collect experimental data. The second series represents the volumetric component of the stored energy for polymer. Again D_i and R_t are determined from experimental data

For an ideally incompressible material, which maintains constant volume

$$J^c = \lambda_1^{\ c}\ \lambda_2^{\ c}\ \lambda_3^{\ c} = J = 1 \text{ and } R(T) = 0 \qquad \text{....(2.6)}$$

Hence, $\lambda_1^{\ c} = \lambda_i$ and $I_1^{\ c} = I_i$

Volumetric series in equation becomes a null series.

The Mooney-Rivlin model, Eqn (2.1) then becomes:

$$U = \sum_{i+j=1}^{N} C_{ij}(I_1 - 3)^i (I_2 - 3)^j ,$$

from this, the Mooney-Rivlin model is often further simplified to an expansion using two terms (N=1). This form is also known as Mooney-Rivlin from and is given as,

$$U = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) \qquad \text{...(2.7)}$$

where,

U = strain energy density function,

C_{10}, C_{01} = Mooney-Rivlin material constants,

$$I_1^c = (\lambda_1\ )^2 + (\lambda_2\ )^2 + (\lambda_3\ )^2 \qquad \text{...(2.8)}$$

$$I_1^c = (\lambda_1\ \ \lambda_2\ )^2 + (\lambda_2\ \ \lambda_3\ )^2 + (\lambda_3\ \ \lambda_1\ )^2 \qquad \text{..(2.9)}$$

Where λ is known as the stretch ratio and is defined as the ratio of deformed to original length. Subscripts 1, 2 and 3 denote three mutually orthogonal x, y and z.

b) Arruda-Boyce form:

The form of the Arruda-Boyce strain energy potential is

$$U = \mu\left\{\frac{1}{2}(\bar{I}_1 - 3) + \frac{1}{20\lambda^2_m}(\bar{I}_1^{-2} - 9) + \frac{11}{1050\lambda^4_m}(\bar{I}_1^{-3} - 9) + \ldots \quad \ldots\ldots\right\} + \frac{1}{D}\left(\frac{J_{el}^2 - 1}{2} - \ln J_{el}\right)$$

...(2.10)

where U is the strain energy per unit reference volume,μ, λ_m and D are temperature-dependent material parameters, $\bar{I}_1$ is the first deviatoric strain invariant defined as

$$\bar{I}_1 = \bar{\lambda}_1^{-2} + \bar{\lambda}_2^{-2} + \bar{\lambda}_3^{-2} \qquad \ldots(2.11)$$

where the deviatoric stretches $\bar{\lambda}_i = J^{-1/3}\lambda_i$, J is the total volume ratio: J_{el} is the elastic volume ratio as defined below in the " thermal expansion" and λ_i are the principle stretch The initial shear modulus is given directly by, while the initial bulk modulus is related to D with the expression

$$K_0 = \frac{2}{D} \qquad \ldots(2.12)$$

if D is zero, the materials fully incompressible.

c) Neo-Hooken form:

The form of the Neo-Hooken strain energy potential is

$$U = C_{10}(\bar{I}_1 - 3) + \frac{1}{D_1}\left(J^{el} - 1\right)^2 \qquad \ldots(2.13)$$

where U is the strain energy per unit reference volume; C_{10} and D_1 are temperature-dependent material parameters; $\bar{I}_1$ is the first deviatoric strain invariant defined as

$$\bar{I}_1 = \bar{\lambda}_1^{-2} + \bar{\lambda}_2^{-2} + \bar{\lambda}_3^{-2} \qquad \ldots(2.14)$$

where the deviatoric stretches $\bar{\lambda}_i = J^{-1/3}\lambda_i$, J is the total volume ratio. J_{el} is the elastic volume ratio as defined below in the " thermal expansion" and λ_i are the principle stretch. The initial shear modulus and bulk modulus are given by

$$\mu_0 = 2C_{10} \qquad \text{and} \qquad K_0 = \frac{2}{D} \qquad (2.15)$$

For cases where the nominal strains are small or only moderately large (<100%), this model usually provides a sufficiently accurate representation. If D_1 is zero, the materials fully incompressible

d) Ogden form

The form of the Ogden strain energy potential is

$$U = \sum_{I=i}^{N} \frac{2\mu_i}{\alpha_i^2}\left(\bar{\lambda}_1^{-\alpha_i} + \bar{\lambda}_2^{-\alpha_i} + \bar{\lambda}_3^{-\alpha_i} - 3\right) + \sum_{i=1}^{N} \frac{1}{D_i}\left(J^{el} - 1\right)^{2i} \qquad (2.16)$$

where the deviatoric stretches $\bar{\lambda}_i = J^{-1/3}\lambda_i$, λ_i are the principle stretch; N is the a material parameter; and μ_i, α_i and D_i are temperature-dependent material parameters. The initial shear modulus and bulk modulus for the Ogden form are given by

$$\mu_0 = \sum_{i=1}^{N} \mu_i \qquad \text{and} \qquad K_0 = \frac{2}{D_1} \qquad ..(2.17)$$

The particular material models described above – the Mooney-Rivlin and Neo-Hooken forms- can be also be obtained from the general Ogden strain energy potential for special choices of μ_i, and α_i.

e) Polynomial form:

The form of polynomial strain energy potential is

$$U = \sum_{i+j=1}^{N} C_{ij}\left(\bar{I}_1 - 3\right)^i \left(\bar{I}_2 - 3\right)^j + \sum_{i=1}^{N} \frac{1}{D_i}\left(J^{el} - 1\right)^{2i} \qquad ..(2.18)$$

where U is the strain energy per unit reference volume; N is a material parameter C_{ij} and D_1 are temperature-dependent material parameters; $\bar{I}_1$ and $\bar{I}_2$ are the first deviatoric strain invariant defined as

$$\bar{I}_1 = \bar{\lambda}_1^{-2} + \bar{\lambda}_2^{-2} + \bar{\lambda}_3^{-2} \quad \text{and} \quad \bar{I}_2 = \bar{\lambda}_1^{-(-2)} + \bar{\lambda}_2^{-(-2)} + \bar{\lambda}_3^{-(-2)} \qquad \ldots(2.19)$$

where the deviatoric stretches $\bar{\lambda}_i = J^{-1/3}\lambda_i$, J is the total volume ratio: J_{el} is the elastic volume ratio as defined below in the " thermal expansion" and λ_i are the principle stretch. The initial shear modulus and bulk modulus are given by

$$\mu_0 = 2(C_{10} + C_{01}) \quad \text{and} \quad K_0 = \frac{2}{D} \qquad \ldots(2.20)$$

For cases where the nominal strains are small or only moderately large (<100%), the first terms in the polynomial series usually provide a sufficiently accurate model. If D_1 is zero, all of the D_i must be zero an the material is fully incompressible. Some particular material models- the Mooney-Rivlin, Neo-Hooken, and Yeoh forms- are obtained for special choices of C_{ij}

f) Reduced polynomial form:

The form of the reduced polynomial strain potential is

$$U = \sum_{i=1}^{N} C_{i0}\left(\bar{I}_1 - 3\right)^i + \sum_{i=1}^{N} \frac{1}{D_i}\left(J^{el} - 1\right)^{2i} \qquad \ldots(2.21)$$

where U is the strain energy per unit reference volume; N is a material parameter C_{i0} and D_1 are temperature-dependent material parameters; $\bar{I}_1$ is are the first deviatoric strain invariant defined as

$$\bar{I}_1 = \bar{\lambda}_1^{-2} + \bar{\lambda}_2^{-2} + \bar{\lambda}_3^{-2} \qquad \ldots(2.22)$$

where the deviatoric stretches $\bar{\lambda}_i = J^{-1/3}\lambda_i$, J is the total volume ratio: J_{el} is the elastic volume ratio as defined below in the " thermal expansion" and λ_i are the principle stretch. The initial shear modulus and bulk modulus are given by

$$\mu_0 = 2(C_{10}) \quad \text{and} \quad K_0 = \frac{2}{D} \qquad \ldots(2.23)$$

For cases where the nominal strains are small or only moderately large (<100%), the first terms in the polynomial series usually provide a sufficiently accurate model. If D_1 is zero, all of the D_i must be zero an the material is fully incompressible

g) Van Der Waals form:

The form of the Van Der Waals strain energy potential is

$$U = \mu\left\{-(\lambda_m^2 - 3)[\ln(1-\eta)+\eta] - \frac{2}{3}a\left(\frac{\overset{''}{I}-3}{2}\right)^{\frac{3}{2}}\right\} + \frac{1}{D}\left(\frac{J_{el}^2-1}{2} - \ln J_{el}\right) \quad \text{...(2.24)}$$

where

$$\overset{''}{I} = (1-\beta)\bar{I}_1 + \beta\bar{I}_2 \text{ and } \eta = \sqrt{\frac{\overset{''}{I}-3}{\lambda_m^2-3}} \quad \text{.. (2.25)}$$

Here, U is the strain energy per unit reference volume; μ is the initial shear modulus: λ_m is the locking stretch; a is the global interaction parameter; β is an invariant mixture parameter; and D governs the compressibility. These parameters can be temperature dependent $\bar{I}_1$ and $\bar{I}_2$ are the first deviatoric strain invariant defined as

$$\bar{I}_1 = \bar{\lambda}_1^{-2} + \bar{\lambda}_2^{-2} + \bar{\lambda}_3^{-2} \text{ and } \bar{I}_2 = \bar{\lambda}_1^{-(-2)} + \bar{\lambda}_2^{-(-2)} + \bar{\lambda}_3^{-(-2)} \quad \text{...(2 26)}$$

where the deviatoric stretches $\bar{\lambda}_i = J^{-1/3}\lambda_i$, J is the total volume ratio: J_{el} is the elastic volume ratio as defined below in the " thermal expansion" and λ_i are the principle stretch. The initial shear modulus and bulk modulus are given by

$$\mu_0 = \mu \quad \text{and} \quad K_0 = \frac{2}{D} \quad \text{...(2.27)}$$

If D is equal to zero, the material is fully incompressible.

h) Yeoh form:

The form of the Yeoh strain energy potential is

$$U = C_{10}\left(\bar{I}_1-3\right) + C_{20}\left(\bar{I}_1-3\right)^2 + C_{30}\left(\bar{I}_1-3\right)^3 + \frac{1}{D_1}\left(J^{el}-1\right)^2 + \frac{1}{D_2}\left(J^{el}-1\right)^4 + \frac{1}{D_3}\left(J^{el}-1\right)^6 \quad ..\ (2.28)$$

where U is the strain energy per unit reference volume; C_{10} and D_1 are temperature-dependent material parameters; $\bar{I}_1$ is are the first deviatoric strain invariant defined as

$$\bar{I}_1 = \bar{\lambda}_1^{-2} + \bar{\lambda}_2^{-2} + \bar{\lambda}_3^{-2} \quad ..(2\ 29)$$

where the deviatoric stretches $\bar{\lambda}_i = J^{-1/3}\lambda_i$, J is the total volume ratio J_{el} is the elastic volume ratio as defined below in the " thermal expansion" and λ_i are the principle stretch The initial shear modulus and bulk modulus are given by

$$\mu_0 = 2(C_{10}) \qquad \text{and} \qquad K_0 = \frac{2}{D} \quad ...(2.30)$$

If D_1 is zero, all of the D_i must be zero an the material is fully incompressible

Finite element analysis of polymer products can be used by designer to determine the stresses and temperature in target application. From these stress values, the weaker sections can be identified and redesign. Even finite element analysis can also be used to predict the performance by determining the design stiffness constants of polymer. But the finite element method has been developed previously to more mature stages for the past many years. The fundamental steps for its application to polymeric products have been understood for perhaps in the last twenty years However except for few cases, its impact on polymeric products appears to have been delayed until recently. This may be because finite element analysis on polymer has certain difficulties, for example.

i) Polymer is nearly incompressible, developing high stress in regions of confinement.

ii) Polymer undergoes large strains, indeed, its compliance is one of its attractions.

iii) Polymer is often bonded to enormously stiffer components.

iv) Failure often occurs at interfaces between polymer and stiff components.

v) Polymer material properties, expressed in the form of strain energy function, are very difficult to characterize experimentally

The stress strain data for ethylene propylene diene polymer (as a representative) are fed and given in appendix A. The material constants of the above strain energy function are evaluated. The best fit curve is predicted by different strain energy potentials from the test data. The Arruda-Boyce form of strain energy potential gives the best fit in all case. A representative plot for ethylene propylene diene polymer is shown in Figure 2.1 using the stress strain data at 25°C.

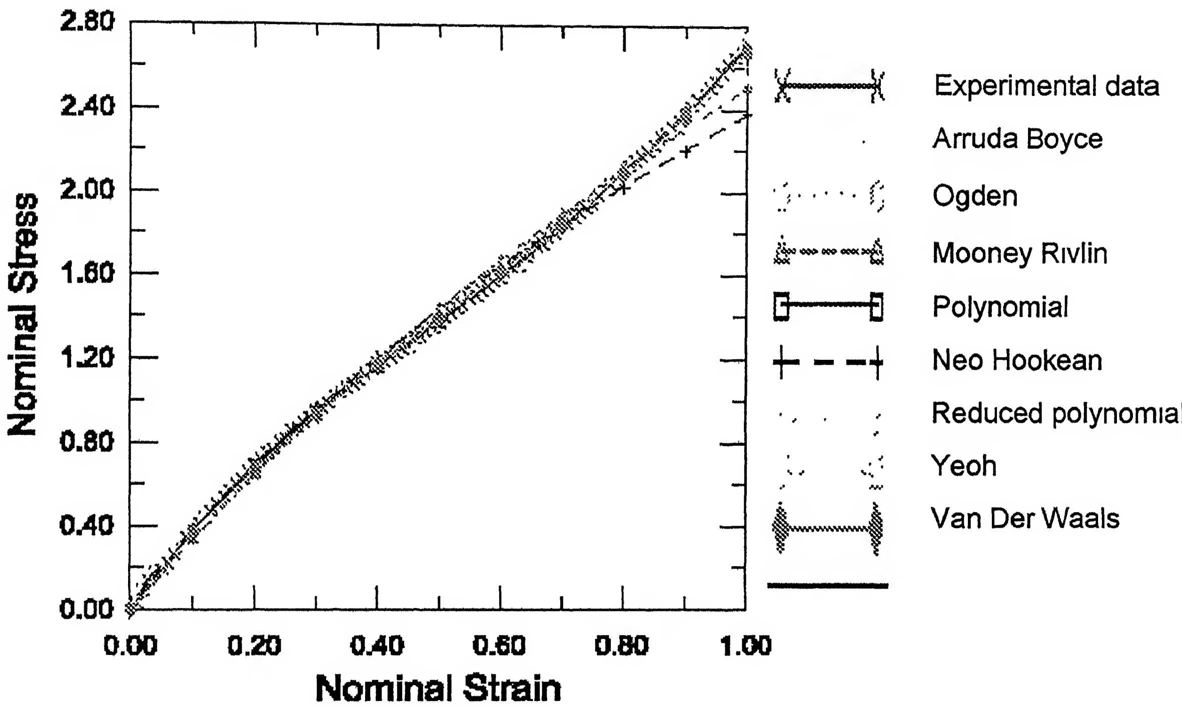


Figure 2.1: Comparison of various strain energy potential form using ethylene propylene diene polymer at 50°C.

In the recent years a number of commercial codes have announced, used or upgraded in the form of a hyper-elastic element These include ABAQUS, ALGOR, ASKA, COSMOS-86, MARK and TEXGAP. All packages involve the following steps.

i) Finite element discretization
ii) Generation of element equations
iii) Assembly of element equations
iv) Verification of convergence
v) Interpretation of results

The first step constitutes the pre-processing stage, second and third steps constitute the solution phase and the fourth and fifth steps constitute the post-processing stage.

2.2: INTRODUCTION TO ABAQUS

The following steps are adopted to optimize the design parameters of seal,

Step 1: Part modeling

Step 2: Material modeling

Step 3: Assembly of the part and material modeling

Step 4: Step modeling

Step 5: Interaction modeling

Step 6: Boundary conditions

Step 7 Mesh modeling

Step 8: Job modeling.

Step 1 Part Modeling: In this step, different parts, i.e., groove, polymeric-seal and the upper surface against which the sealing has been made according to the corresponding dimensions as given in Figures 1 1 to 1 3 (Described in Chapter 1).

Step 2 Material Modeling: In this step, material and sections are defined and section is assigned to different parts made in the previous step. A section is assigned to the par instance. It contains information about the properties of a part or a region of a part. When a section is assigned to the part, the software automatically assigns that section to each instance of the part. Section definition refers to material also.

In the present section model, two sections have been defined. First, steel section which is a homogeneous solid section with steel as the material and it has been assigned to the groove. Second, polymer section, which is also homogeneous solid section with rubber as material and it has been assigned to seal. The upper surface which is analytical rigid does not need any section definition in this mode. The properties of the above materials are defined below

Steel: It is defined as elastic material having a Young's Modulus of 209 E3 MPa and Poisson's ratio of 3

Polymer: It has been defined as hyperelastic material. For defining hyperelastic material in finite element analysis, it is necessary to define strain energy potential. The commonly used strain energy potentials in this analysis are Arruda-Boyce, Mooney-Rivlin, Neo-Hooken, Ogden, Polynomial, Reduced Polynomial, Van Der Waals, Yeoh, etc.

Step 3 Assembly of the Part and Material Modeling: When a part is created, it exists in its own coordinate system, independent of other parts in the model In the present step, it creates instances of the parts and to position the sequentially applying position constraints that align selected feces or edges or by applying simple translations and rotations. A part instance is a representation of the original part. An instance maintains its association with the original part. If geometry of a part changes, software automatically updates all instances to reflect these changes. In the current model, parts are axisymmetric and they can be moved only along the axis and not in any other direction.

Step 4 Step Modeling: A sequence one or more types of analysis are defined in this step. The software creates a special initial step at the beginning of the model's step sequence and names it Initial. In the initial step, boundary conditions and interactions that are applicable at the very beginning of the analysis are defined. In the present model, all the boundary condition and interactions have been applied in the initial step. The initial step followed by one or more analysis. Each analysis step is associated with a specific analysis procedure. In the present model there is only one analysis which results the inflation behaviour of the seal. A geometric non-linearity was introduced the analysis.

Step 5 Interaction Modeling: The contact between two surfaces has been defined in this step. The friction coefficient between all the mating surfaces is μ = 0 2.

Step 6 Boundary Conditions: In this step, loads and boundary conditions are applied The assembled model with inflation pressure and boundary conditions applied is shown in the Figure **2.2.** Since the model is axisymmetric so it has three degree of freedom- translation along the x-axis, translation along the y-axis and rotation about z-axis. Fixed boundary conditions are applied at bottom of the groove The same has been done for the upper surface is a rigid surface applying boundary condition.

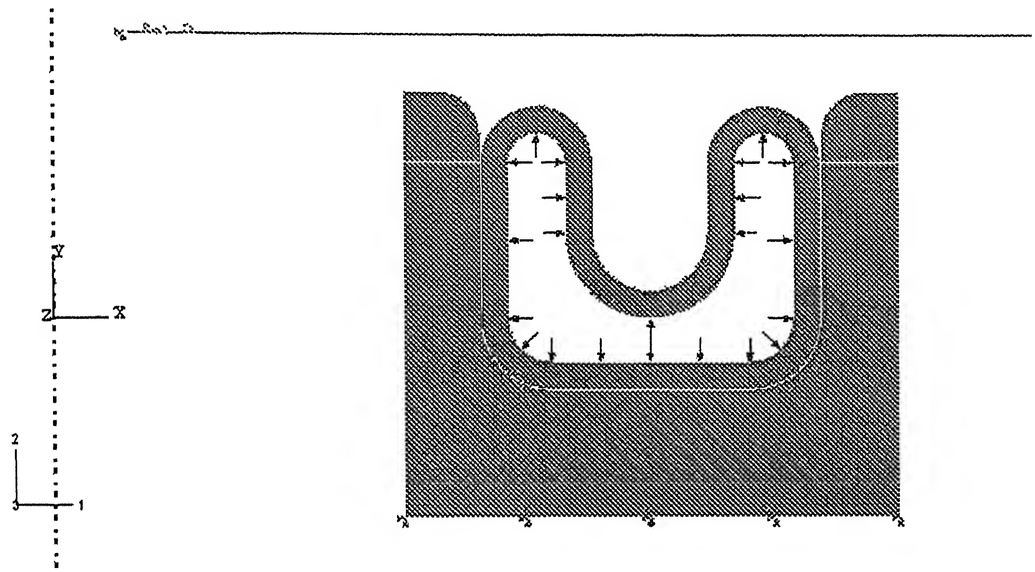


Figure 2.2. Assembled model with applied pressure and boundary conditions

Step 7 Mesh Modeling: Mesh has been generated on assemblies by free meshing technique using quadrilateral elements this step. The meshed assembly is shown in Figure 2.3 . Geometric order of the element used is linear.

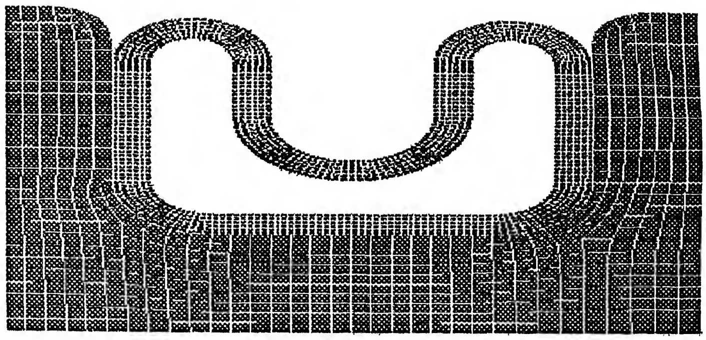


Figure-2.3: Meshed assembly

Step 8 Job Modeling: In this step, total FEM model has been solved i.e. submitted for the analysis and progress is monitored. Once analysis completed results are post-processed and presented.

2.3: VALIDITY OF ABAQUS SOFTWARE:

The validity of ABAQUS software is shown in Appendix B

CHAPTER 3

FINITE ELEMENT ANALYSIS OF UNBEADED SEAL

3.1: ANALYSIS OF SEAL UNDER STATIC CONDITION

In the static condition the load acting on the seal is inflation pressure. Various geometries of scales are studied with different pressure.

3.1.1: MODELLING OF SEAL

The analysis of the seals are carried out for two polymers (ethylene propylene diene polymer, fluorocarbon using finite element package ABAQUS. In static condition, the loads acting on the seal is inflation pressure and there is no load in third direction and hence, problem can be solved as a 2-D problem. An equivalent 2-D model is created and the analysis is carried out by taking the advantage of the symmetry of the problem, the problem can be solved as a plane strain problem. The contact has been established with the 2-D elements

The terminology used is shown in Figure 3.1. Initially, the analysis is carried out by fixing the entire seal. The seal fails at lower load, because the outer surface is fixed and only the inner surface expands with the inflated pressure. Then a small gap of .1 mm on either side is given to allow the free expansion of the seal. The analysis is carried out by varying the side gap upto 1 mm on either side. There was not much difference in the results as the gap is increased, the seal width is decreasing because of the seal groove width is fixed.

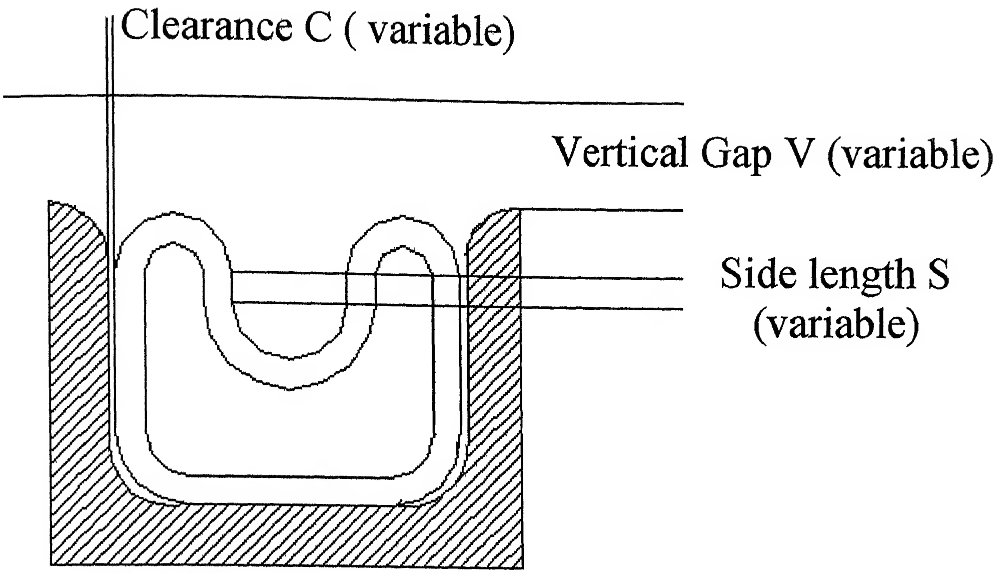


Figure 1: Terminology used for unbeaded seal

3.1.2: ANALYSIS PROCEDURE

Analysis is carried out by using a finite element package ABAQUS. The problem comes under the non-linear and contact type. The model of the seal is created as per the dimensions. Elements are selected depending on the materials Since the material of the seal is hyperelastic, a CAX4H element is used for polymeric material. CAX4 elements are used for steel groove material and upper surface is analytical rigid and non-deformable surface.

As stresses in the seal are important, seal portion is meshed with fine mesh and groove portion is meshed with coarse mesh.

A contact pair has to be established in order to stop the expansion of the seal at the target surface. There are several types of contacts like node-surface contact, node-node contact and surface-surface contact. This problem comes under the surface-to-surface contact.

The load acting on the seal are internal pressure i.e. inflation pressure. As the material of the seal is sensitive, we use Static Risk option in which load is applied in number of substeps with small increments. The pressure is applied on the inner surface of the seal uniformly. All the movement of the seal groove and upper surface are arrested

3.1.3: LOADS ON THE SEAL

The loads acting on the seal is inflation pressure. The inflation pressure is different conditions. The maximum inflation pressure, the seal should withstand in static condition is 200 kPa and dynamic condition, it is 50 kPa. Hence the material is very sensitive, the load should no applied at a time The load is applied in substeps, which are point points within a load step at which solutions are calculated by applying the loads gradually so that an accurate solution can be obtained. If the numbers of substeps are less, then it is not possible to predict the failure of the seal correctly and if the numbers of substeps are more then run time will more. So, static risk in which numbers of substeps automatically adjust are chosen here.

3.1.4: BOUNDARY CONDITIONS

The boundary conditions for the problem are seal groove and upper surface are completely fixed and seal is axi-symmetric The seal bottom is glued to the seal groove.

3.1.5: MATERIAL PROPERTIES:

As it was mentioned the material used for the seal is EPDM and FKM polymer The properties that have been considered in the analysis for this material are shown in Table 3.1

Table 3 1: Material properties of EPDM and FKM at 50°C

Material	EPDM	FKM
Young's modulus	4 MPa	4 5 MPa
Poisson's ratio	0 46	0.48
Density	1210 kg / m^3	1120 kg/m^3
Shear modulus	1.36 MPa	1.40 MPa
Thermal conductivity	0.2 W/m-K	-
Tensile strength	9 5 MPa	6 5 MPa
Co-efficient of linear expansion	250 x 10^{-6} m/ m-K	-

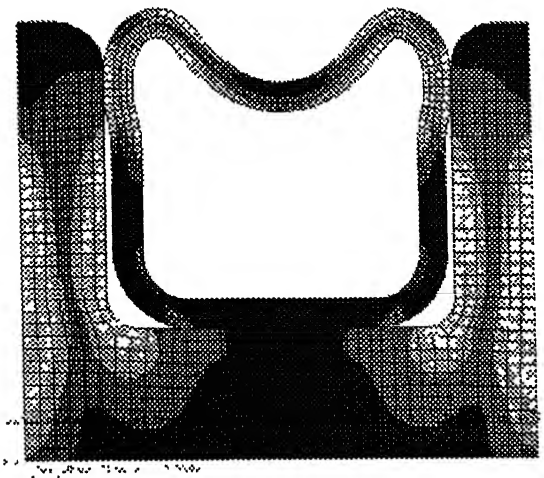
3.1.6: Parameters under study

In the analysis of the seal many parameters are varied inorder to find the suitable dimensions of seal to withstand the specified pressure. These are given below

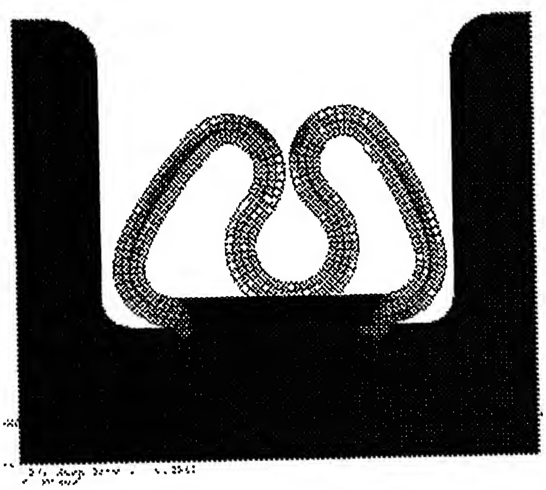
- Two types of polymer are used. These are EPDM and FKM
- Thickness of seal is varied from 1.0 to 3 0 mm insteps of 0 2 mm
- Vertical gap between seal surface and top cover is varied from 3 to 4 mm insteps of 1.0 mm
- Side gap between the seal and the seal groove is varied from zero to 1.0 mm on both the sides insteps of 0.2 mm.
- Side length of seal is varied from 1.0 to 5 mm in steps of 1mm
- Inflation pressure varies from 10 to 50 kPa
- Coefficient of friction varies from 0.1 to .9

Few representative figures obtained under static condition from finite element analysis are shown in the next section

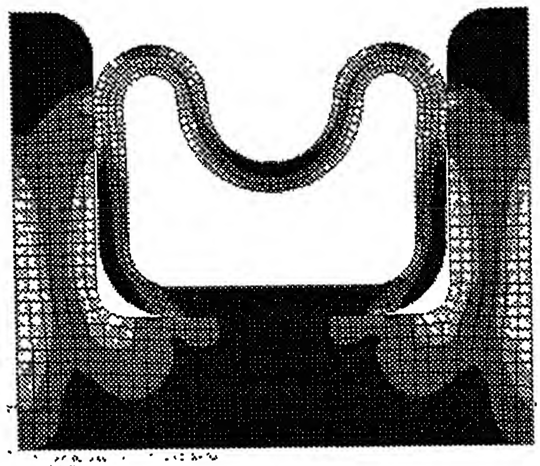
MATERIAL=EPDM, SEAL GAP (G)=3,
WIDTH (W) = 23.5, VERTICAL HEIGHT (VL) = 18,
SIDE LENGTH (S) =1
INNER PRESSURE (P) = 22 kPa
CONTACT PRESSURE= 0 kPa
MAXIMUM STRESS=
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



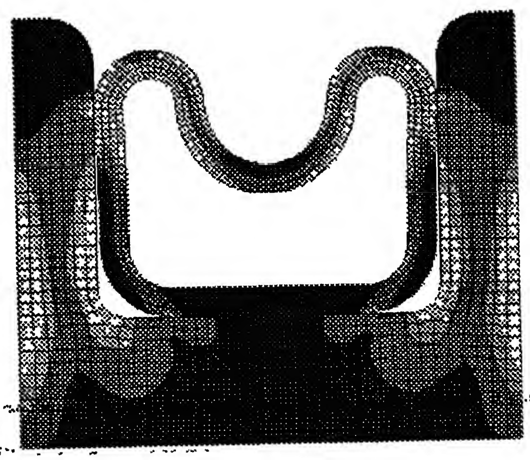
MATERIAL=EPDM, SEAL GAP (G)=3,
WIDTH (W) = 23.5, VERTICAL HEIGHT (VL) = 18, SIDE LENGTH (S) =1
INNER PRESSURE (P) = 25 kPa
CONTACT PRESSURE= 0kPa
MAXIMUM STRESS=0 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



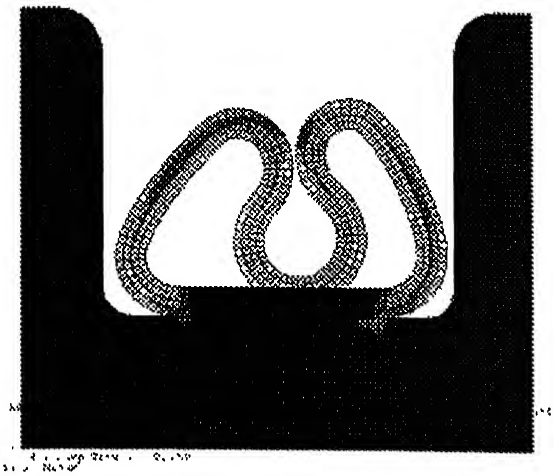
MATERIAL=FKM SEAL GAP (G) =3,
WIDTH (W)= 23.5, VERTICAL HEIGHT (VL) =18,
SIDE LENGTH (S) = 1
INNER PRESSURE (P) = 22 kPa
CONTACT PRESSURE= 0 kPa
MAXIMUM STRESS=
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



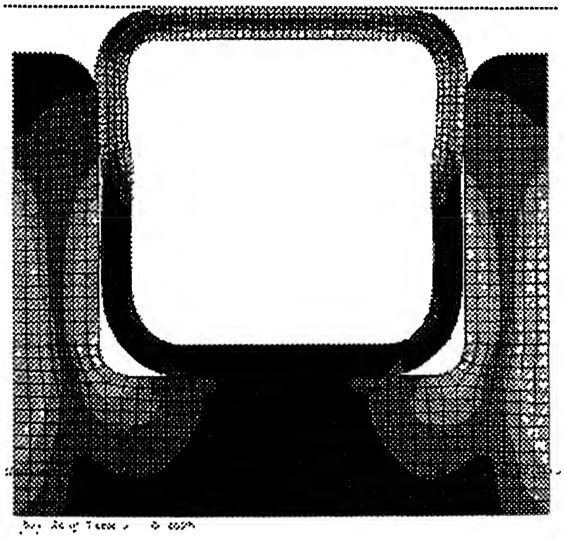
MATERIAL=FKM, SEAL GAP (G) = 3,
WIDTH (W) = 23.5, VERTICAL HEIGHT (VL) = 18,
SIDE LENGTH (S) =1
INNER PRESSURE (P) = 23 kPa
CONTACT PRESSURE=0 kPa
MAXIMUM STRESS=0 MPa
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



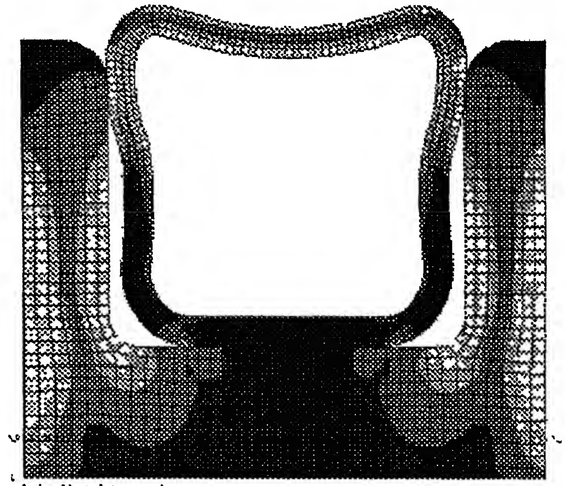
MATERIAL=EPDM, SEAL GAP (G)=3, WIDTH (W) = 23.5, VERTICAL HEIGHT (VL) = 18,
SIDE LENGTH (S) =1
INNER PRESSURE (P) = 26 kPa
CONTACT PRESSURE=0kPa
MAXIMUM STRESS=
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



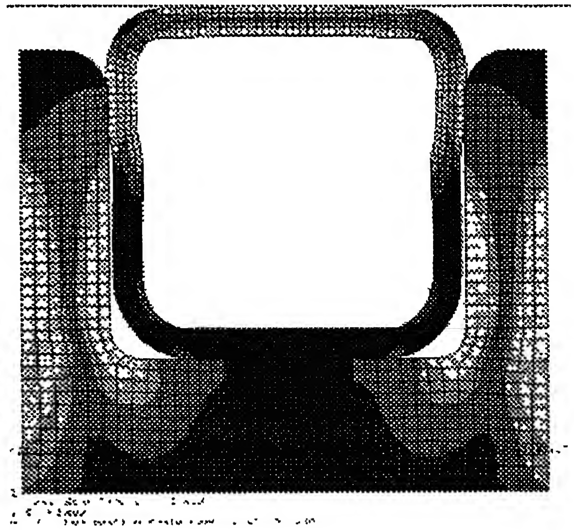
MATERIAL=EPDM, SEAL GAP (G)=3, WIDTH (W) = 23.5, VERTICAL HEIGHT (VL) = 18, SIDE LENGTH (S) =1
INNER PRESSURE (P) = 27 kPa
CONTACT PRESSURE=35.4 kPA
MAXIMUM STRESS=1.88 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



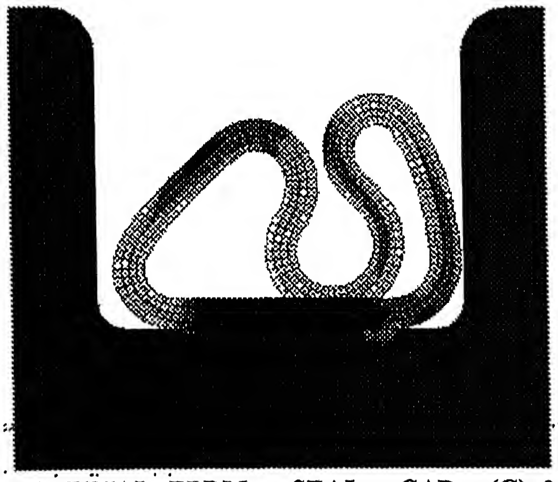
MATERIAL=FKM, SEAL GAP (G) = 3, WIDTH (W) = 23.5, VERTICAL HEIGHT (VL)=18,
SIDE LENGTH(S) =1
INNER PRESSURE (P) = 29 kPa,
CONTACT PRESSURE=0kPa
MAXIMUM STRESS=
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



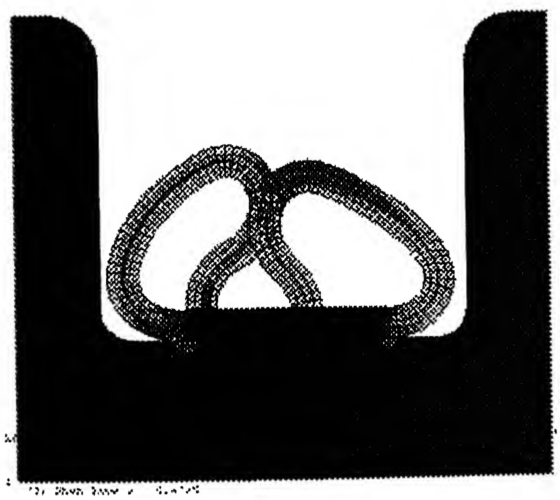
MATERIAL=FKM, SEAL GAP (G) = 3, WIDTH (W) = 23.5, VERTICAL HEIGHT (VL)=18, SIDE LENGTH(S) =1
INNER PRESSURE (P) = 30 kPa, CONTACT PRESSURE=40.2 kPa
MAXIMUM STRESS=2.3 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



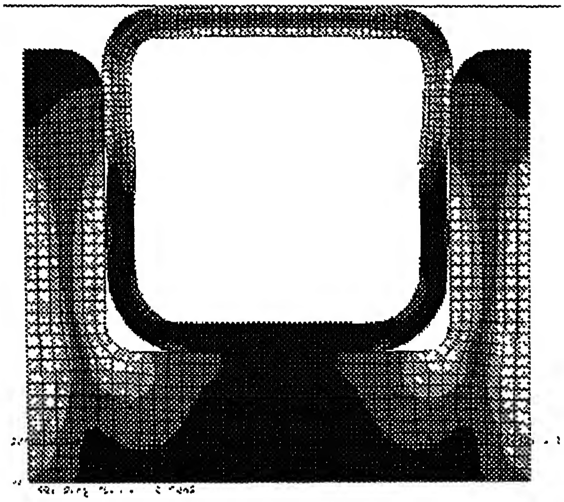
MATERIAL=EPDM, SEAL GAP (G)=3, WIDTH (W) = 23.5, VERTICAL HEIGHT (VL) = 18,
SIDE LENGTH (S) =1
INNER PRESSURE (P) = 29 kPa
CONTACT PRESSURE=0kPa
MAXIMUM STRESS=........
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



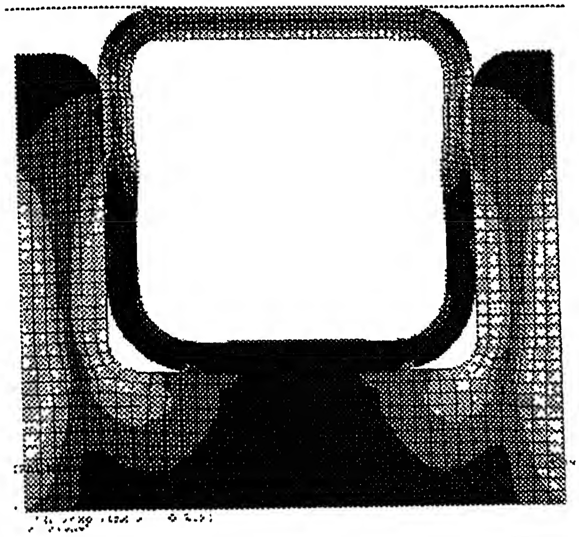
MATERIAL=EPDM, SEAL GAP (G)=3, WIDTH (W) = 23.5, VERTICAL HEIGHT (VL) = 18,
SIDE LENGTH (S) =1
INNER PRESSURE (P) = 30 kPa
CONTACT PRESSURE=0kPa
MAXIMUM STRESS=........
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



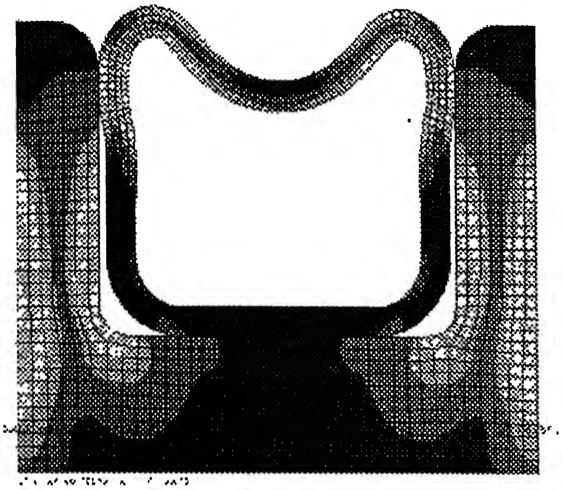
MATERIAL=FKM, SEAL GAP (G) = 3, WIDTH (W) = 23.5, VERTICAL HEIGHT (VL)=18,
SIDE LENGTH(S) =1
INNER PRESSURE (P) = 35 kPa, CONTACT PRESSURE=41.6 kPa
MAXIMUM STRESS=2.3 MPa
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



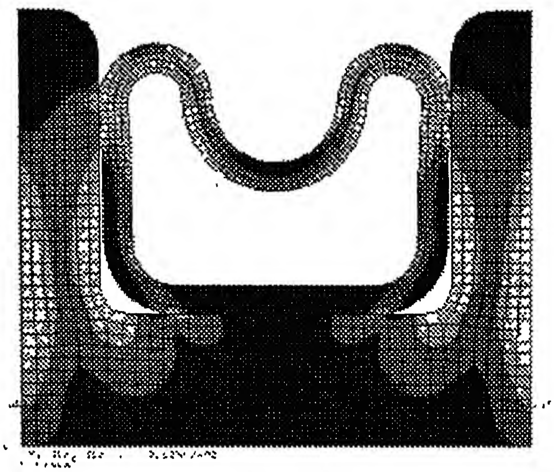
MATERIAL=EPDM, SEAL GAP (G)=3, WIDTH (W) = 23.5, VERTICAL HEIGHT (VL) = 18,
SIDE LENGTH (S) =1
INNER PRESSURE (P) = 40 kPa
CONTACT PRESSURE=42.8 kPA
MAXIMUM STRESS=1.98 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50^{o}C
COEFFICIENT OF FRICTION=0.2



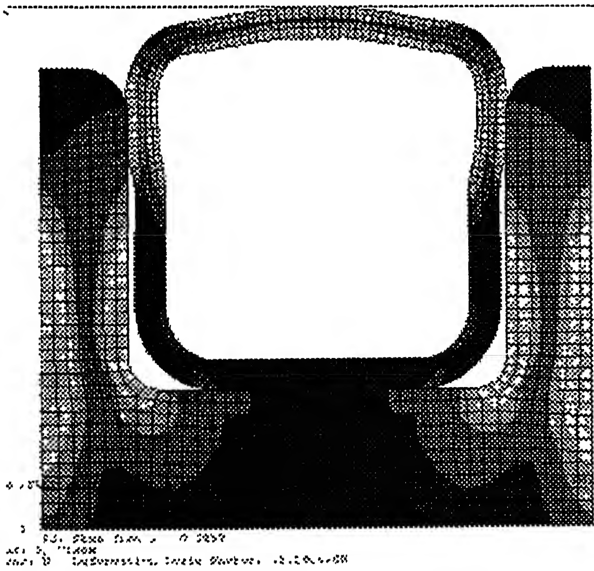
MATERIAL=EPDM, SEAL GAP (G)= 4,
WIDTH (W) = 23.5, VERTICAL HEIGHT (VL) = 18,
SIDE LENGTH (S) = 1
INNER PRESSURE (P) = 22 kPa
CONTACT PRESSURE=0kPa
MAXIMUM STRESS=……..
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



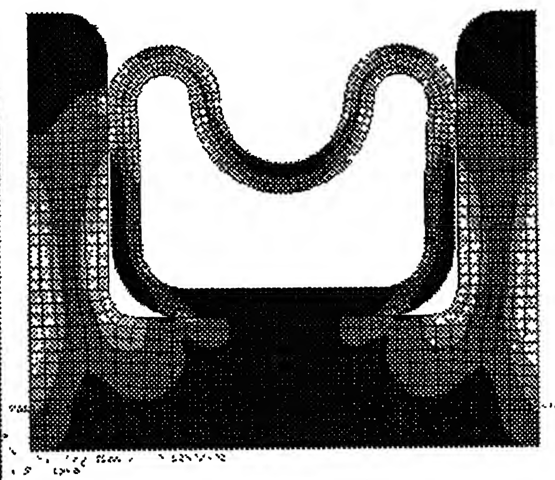
MATERIAL=FKM, SEAL GAP (G)=4,
WIDTH (W)=23.5, VERTICAL HEIGHT (VL) = 18,
SIDE LENGTH (S) =1
INNER PRESSURE (P) = 22 kPa
CONTACT PRESSURE=0kPa
MAXIMUM STRESS=……..
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



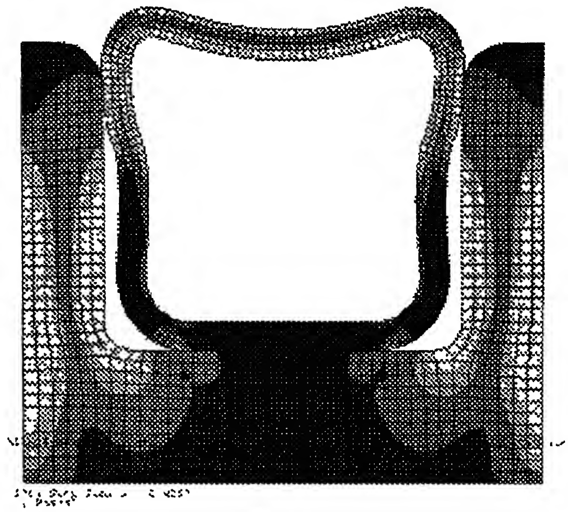
MATERIAL=EPDM , SEAL GAP (G)= 4,
WIDTH (W) = 23.5, VERTICAL HEIGHT (VL) =18,
SIDE LENGTH (S) = 1
INNER PRESSURE (P) = 23 kPa
CONTACT PRESSURE=69.8 kPa
MAXIMUM STRESS=1.8 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



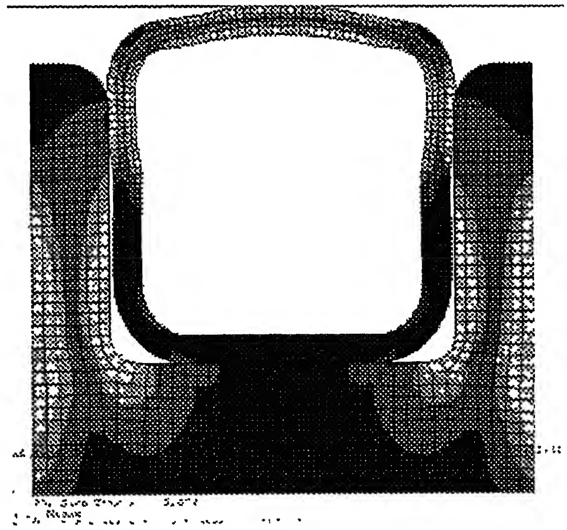
MATERIAL=FKM, SEAL GAP (G) = 4,
WIDTH (W) = 23.5, VERTICAL HEIGHT (VL)=18,
SIDE LENGTH(S) =1
INNER PRESSURE (P) = 23 kPa
CONTACT PRESSURE=0kPa
MAXIMUM STRESS=……..
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



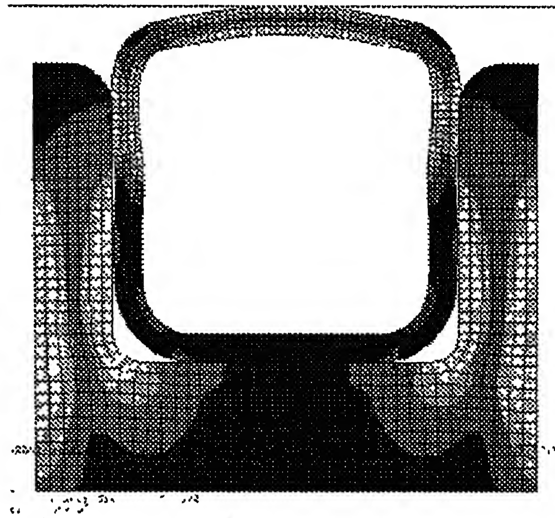
MATERIAL=FKM, SEAL GAP (G) = 4,
WIDTH (W) = 23.5, VERTICAL HEIGHT (VL)=18,
SIDE LENGTH(S) =1
INNER PRESSURE (P) = 29 kPa,
CONTACT PRESSURE=0kPa
MAXIMUM STRESS=........
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50^{O}C
COEFFICIENT OF FRICTION=0.2



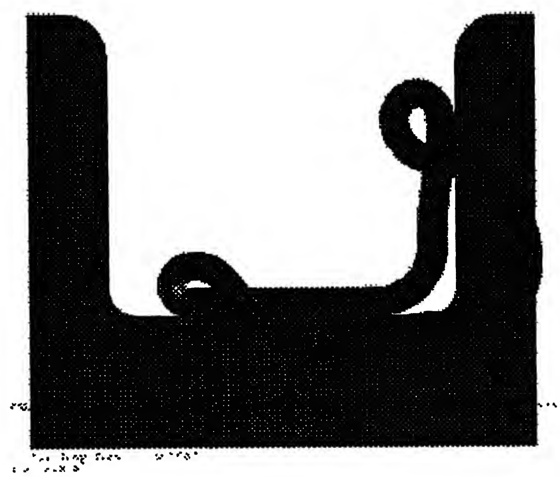
REACTOR=FBTR, MATERIAL=FKM, SEAL GAP (G) = 4, WIDTH (W) = 23.5, VERTICAL HEIGHT (VL)=18,
SIDE LENGTH(S) =1
INNER PRESSURE (P) = 30 kPa, CONTACT PRESSURE=39.4 kPa
MAXIMUM STRESS=2.2MPa
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50^{O}C
COEFFICIENT OF FRICTION=0.2



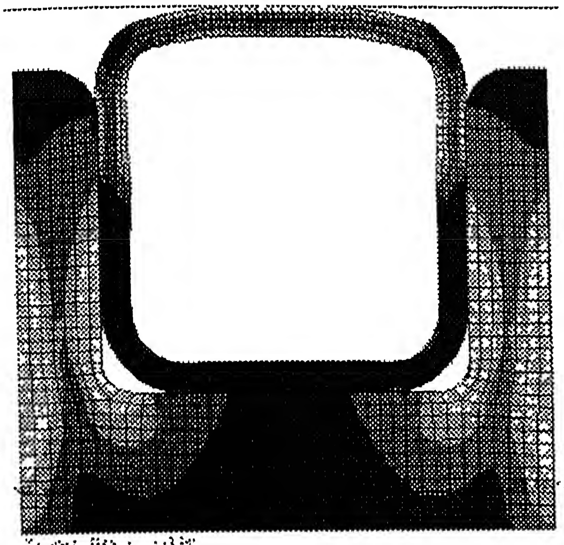
MATERIAL=FKM, SEAL GAP (G) = 4,
WIDTH (W) = 23.5, VERTICAL HEIGHT (VL)=18,
SIDE LENGTH(S) =1
INNER PRESSURE (P) = 35 kPa, CONTACT PRESSURE=73.2 kPa
MAXIMUM STRESS=2.3 MPa
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



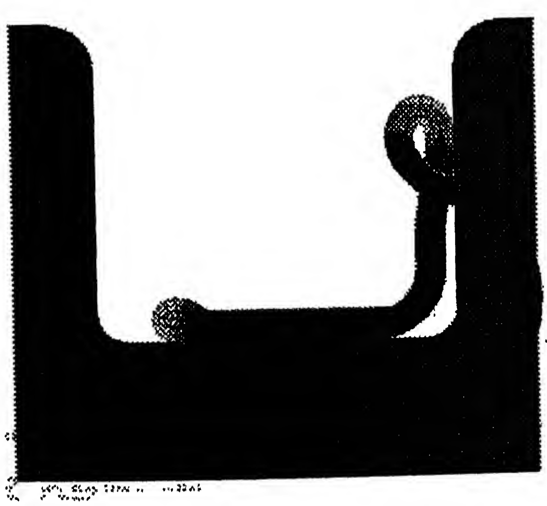
MATERIAL=FKM, SEAL GAP (G) = 4,
WIDTH (W) = 23.5, VERTICAL HEIGHT (VL)=18,
SIDE LENGTH(S) =1
INNER PRESSURE (P) = 40 kPa
CONTACT PRESSURE=.....
MAXIMUM STRESS=........
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



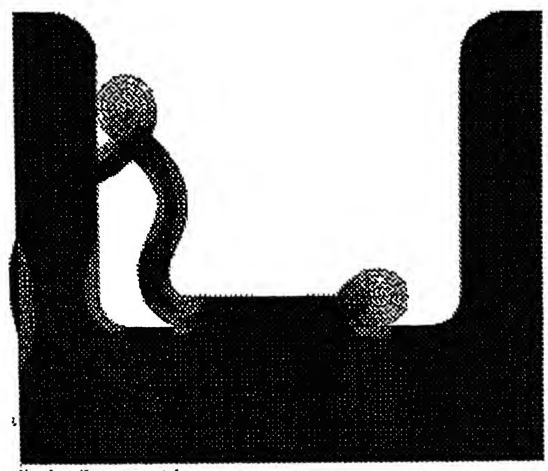
MATERIAL=EPDM
SEAL GAP (G)= 4, WIDTH (W) = 23.5,
VERTICAL HEIGHT (VL) =18,
SIDE LENGTH (S) = 1
INNER PRESSURE (P) = 51 kPa
CONTACT PRESSURE=76.1 kPa
MAXIMUM STRESS=2.1 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



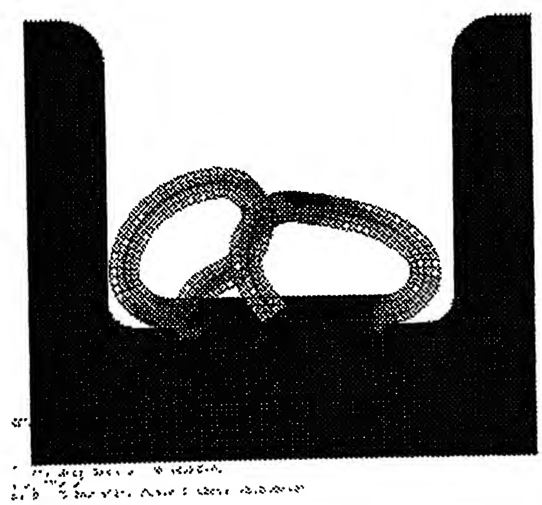
MATERIAL=EPDM, SEAL GAP (G)= 4,
WIDTH (W) = 23.5, VERTICAL HEIGHT
(VL) =18,
SIDE LENGTH (S) = 1
INNER PRESSURE (P) = 52 kPa
CONTACT PRESSURE=0kPa
MAXIMUM STRESS=.....
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



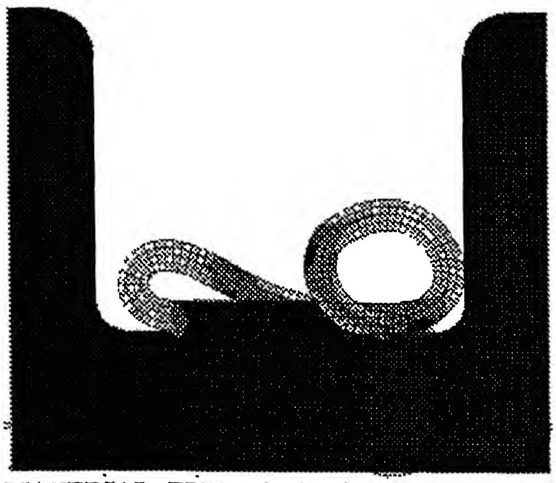
MATERIAL=FKM, SEAL GAP (G) = 4,
WIDTH (W) = 23.5, VERTICAL HEIGHT
(VL)=18,
SIDE LENGTH(S) =1
INNER PRESSURE (P) = 50 kPa
CONTACT PRESSURE=.....
MAXIMUM STRESS=........
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



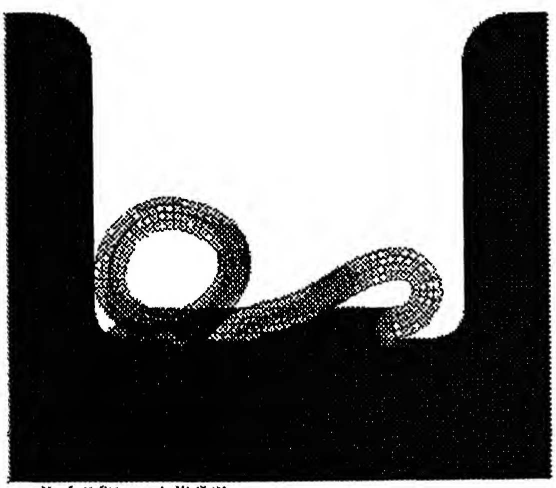
MATERIAL=FKM, SEAL GAP (G) = 4,
WIDTH (W) = 23.5, VERTICAL HEIGHT
(VL)=18, SIDE LENGTH(S) =1
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE=0kPa
MAXIMUM STRESS=........
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



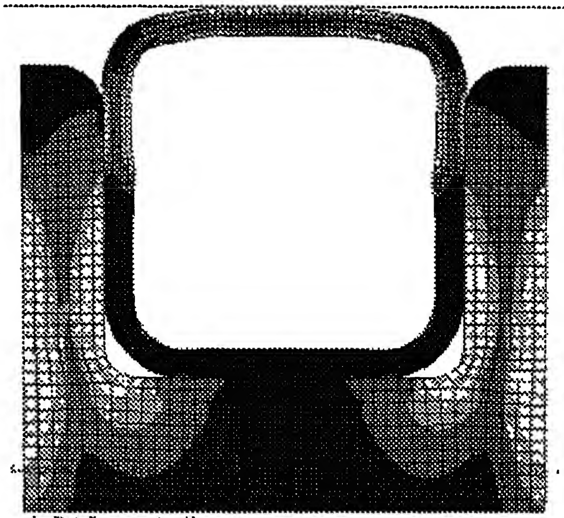
MATERIAL=EPDM, SEAL GAP (G)= 4,
WIDTH (W) = 23.5, VERTICAL HEIGHT (VL) =18,
SIDE LENGTH (S) = 1
INNER PRESSURE (P) = 53 kPa
CONTACT PRESSURE=0kPa
MAXIMUM STRESS=.....
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



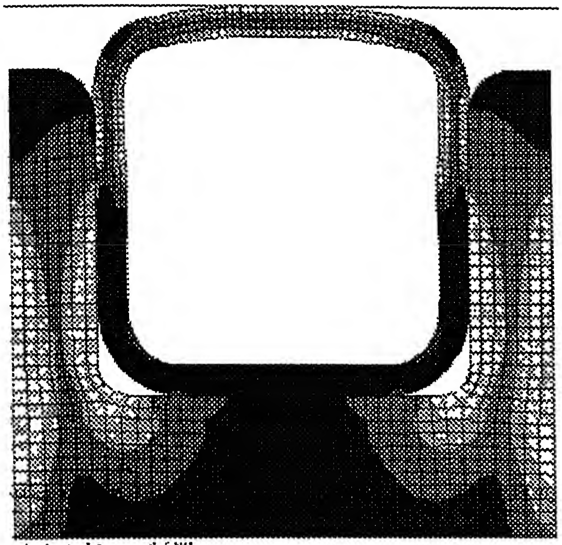
MATERIAL=EPDM, SEAL GAP (G)= 4,
WIDTH (W) = 23.5, VERTICAL HEIGHT (VL) =18,
SIDE LENGTH (S) = 1
INNER PRESSURE (P) = 54 kPa
CONTACT PRESSURE=0kPa
MAXIMUM STRESS=.....
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



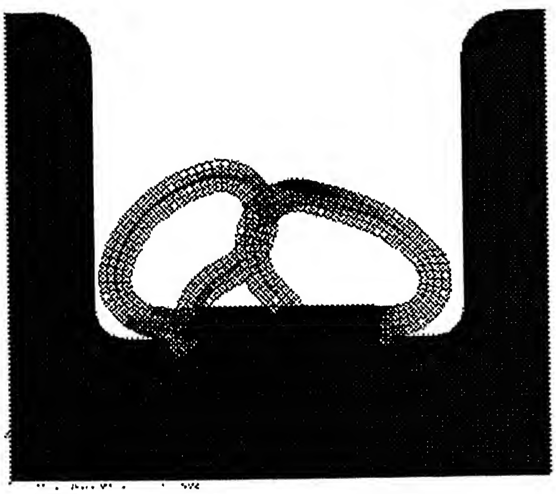
MATERIAL=FKM, SEAL GAP (G) = 4,
WIDTH (W) = 23.5, VERTICAL HEIGHT (VL)=18,
SIDE LENGTH(S) =1
INNER PRESSURE (P) = 70 kPa
CONTACT PRESSURE=110 kPa
MAXIMUM STRESS=2.6 MPa
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



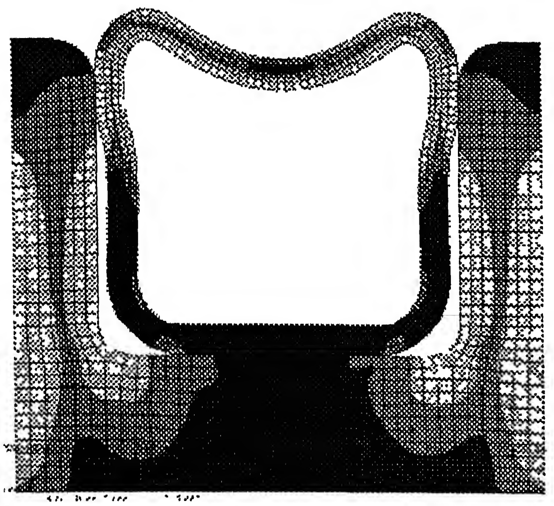
MATERIAL=EPDM
SEAL GAP (G)= 4, WIDTH (W) = 23.5,
VERTICAL HEIGHT (VL) =18,
SIDE LENGTH (S) = 1
INNER PRESSURE (P) = 55 kPa
CONTACT PRESSURE=74.9 kPa
MAXIMUM STRESS=.....2.1 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



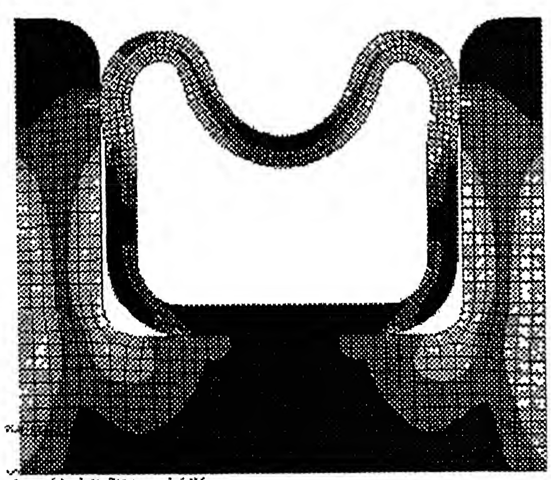
MATERIAL=EPDM, SEAL GAP(G)=4,
WIDTH(W)=23.5, VERTICAL HEIGHT (VL) =18, SIDE LENGTH (S) = 1
INNER PRESSURE (P) = 56 kPa
CONTACT PRESSURE=0kPa
MAXIMUM STRESS=.....
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



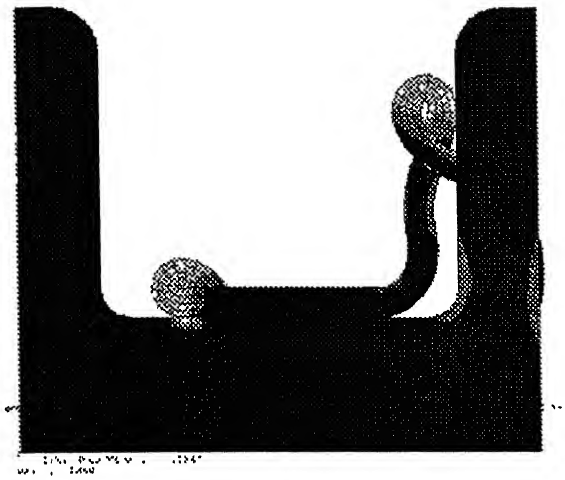
MATERIAL=EPDM, SEAL GAP (G)= 4,
WIDTH (W) = 23.5, VERTICAL HEIGHT
(VL) =18,
SIDE LENGTH (S) = 1
INNER PRESSURE (P) = 57 kPa
CONTACT PRESSURE=0kPa
MAXIMUM STRESS=.....
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



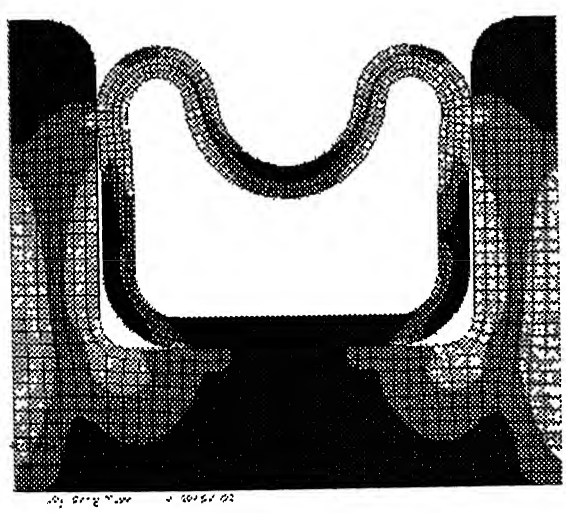
MATERIAL=EPDM, SEAL GAP (G)= 4,
WIDTH (W) = 23.5, VERTICAL HEIGHT
(VL) =18,
SIDE LENGTH (S) = 1
INNER PRESSURE (P) = 58 kPa
CONTACT PRESSURE=0kPa
MAXIMUM STRESS=.....
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



MATERIAL=EPDM
SEAL GAP (G)= 4, WIDTH (W) = 23.5,
VERTICAL HEIGHT (VL) =18,
SIDE LENGTH (S) = 1
INNER PRESSURE (P) = 59 kPa
CONTACT PRESSURE=0kPa
MAXIMUM STRESS=.....
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50^{o}C
COEFFICIENT OF FRICTION=0.2



MATERIAL=EPDM
SEAL GAP (G)= 4, WIDTH (W) = 23.5,
VERTICAL HEIGHT (VL) =18,
SIDE LENGTH (S) = 1
INNER PRESSURE (P) = 61 kPa
CONTACT PRESSURE=0kPa
MAXIMUM STRESS=.....
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50^{o}C
COEFFICIENT OF FRICTION=0.2



3.2: ANALYSIS OF SEAL UNDER DYANAMIC CONDITION

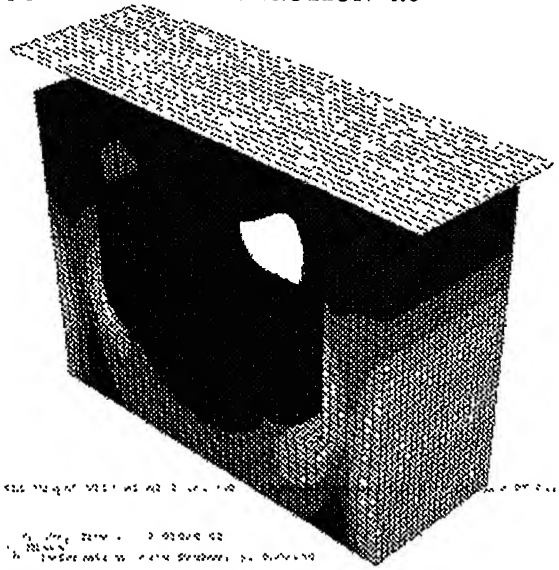
Under dynamic condition, the top cover of the seal will be rotating at a speed of 75 mm/s. Because of this rotation, a tangential load will act on the seal Hence the load acting in third direction, It is not possible to analysis the seal with 2-D model. By taking the advantage of the symmetry of the seal, a small element of seal is considered for analysis

In this analysis there will be no change in element selection, CAX4H for seal and CAX4 for groove. The maximum inflation pressure under dynamic condition is 50 kPa. In this analysis the inflation pressure in the seal and the rotation in seal groove is given in single step. Otherwise the inflation pressure in inner surface of seal is applied when the groove rotates. The bottom part of seal is fixed with groove. The seal will also rotate with respect to the upper surface.

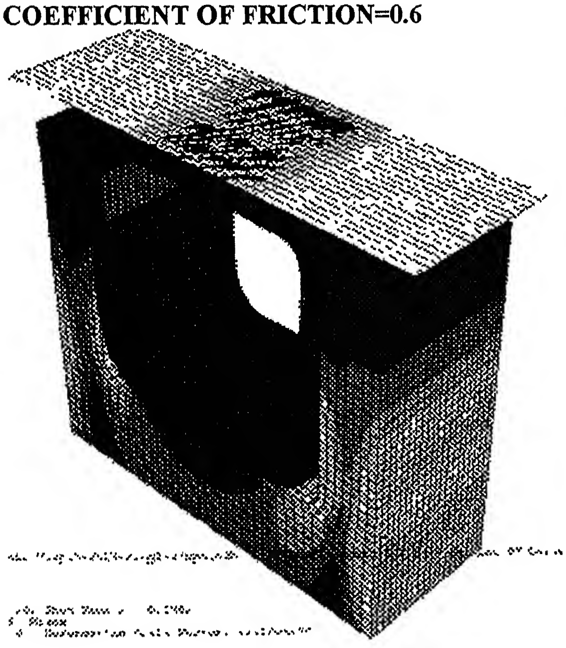
The seal dimensions used under these investigations are optimum dimensions obtained under static condition. Here, the variable parameter is inflation pressure.

Few representative figures obtained under dynamic condition from finite element analysis are shown in the next section

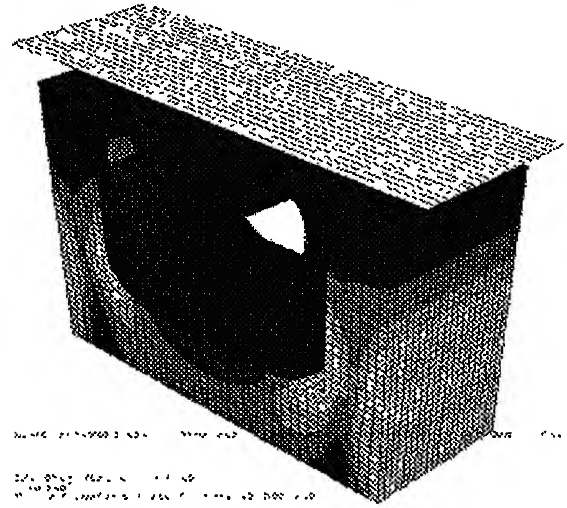
MATERIAL=EPDM, SEAL GAP (G)=3, WIDTH (W) = 23.5, VERTICAL HEIGHT (VL) = 18, SIDE LENGTH (S) =1
INNER PRESSURE (P) = 23 kPa
CONTACT PRESSURE=0kPa
MAXIMUM STRESS=........
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.6



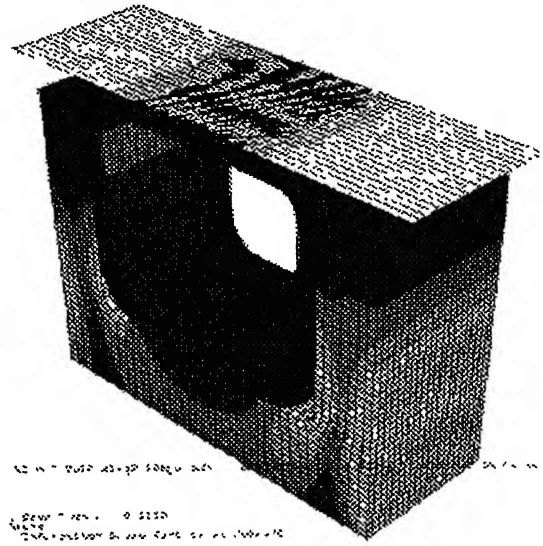
MATERIAL=EPDM, SEAL GAP (G)=3, WIDTH (W) = 23.5, VERTICAL HEIGHT (VL) = 18, SIDE LENGTH (S) =1
INNER PRESSURE (P) = 30 kPa, CONTACT PRESSURE = 36.9 kPa, MAXIMUM STRESS = 1.9 MPa, ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.6



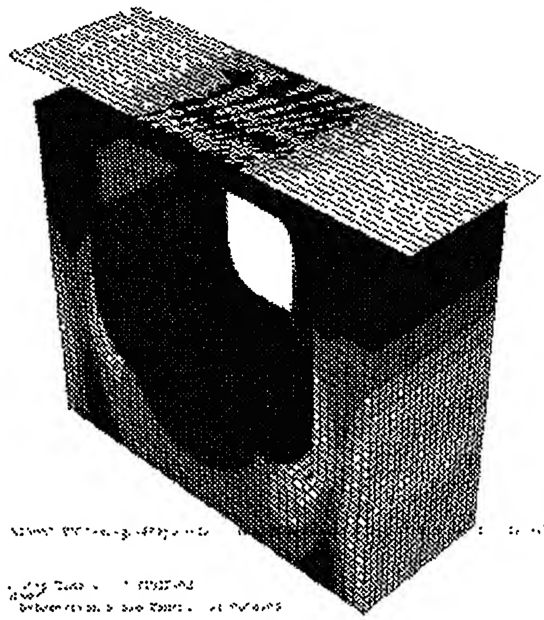
MATERIAL=FKM, SEAL GAP (G)=3, WIDTH (W) = 23.5, VERTICAL HEIGHT (VL) = 18, SIDE LENGTH (S) =1
INNER PRESSURE (P) = 23 kPa
CONTACT PRESSURE=0kPa
MAXIMUM STRESS=........
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.6



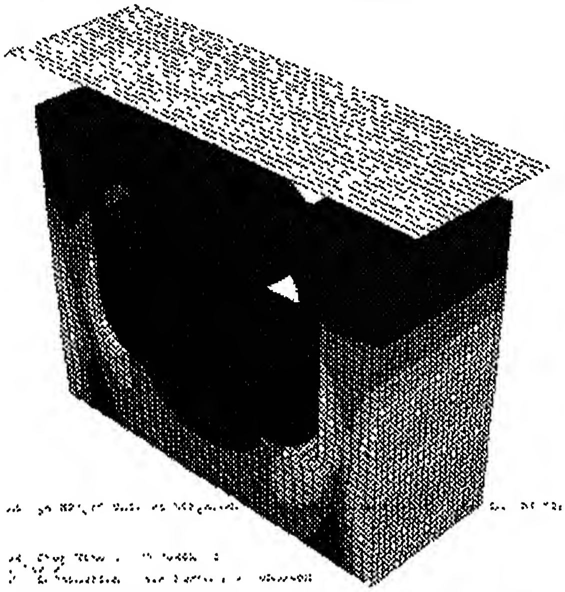
MATERIAL=FKM, SEAL GAP (G)=3, WIDTH (W) = 23.5, VERTICAL HEIGHT (VL) = 18, SIDE LENGTH (S) =1
INNER PRESSURE (P) = 40 kPa, CONTACT PRESSURE = 51.5 kPa, MAXIMUM STRESS = 2.4 MPa, ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.6



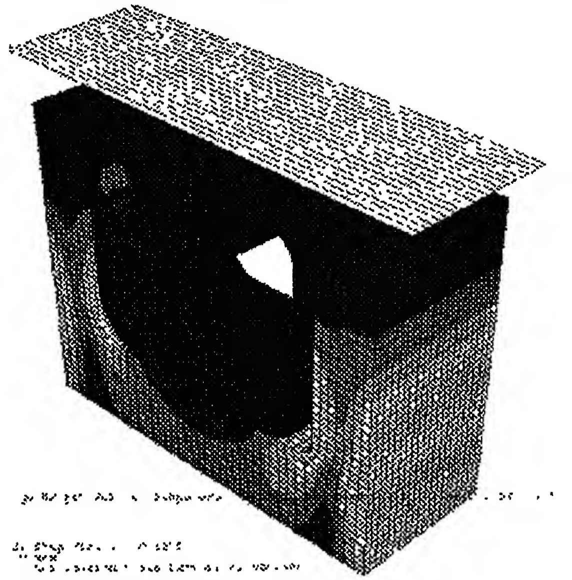
MATERIAL=FKM, SEAL GAP (G)=3, WIDTH (W) = 23.5, VERTICAL HEIGHT (VL) = 18,
SIDE LENGTH (S) =1
INNER PRESSURE (P) = 45 kPa
CONTACT PRESSURE = 46 kPa
MAXIMUM STRESS = 2.4 MPa
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.6



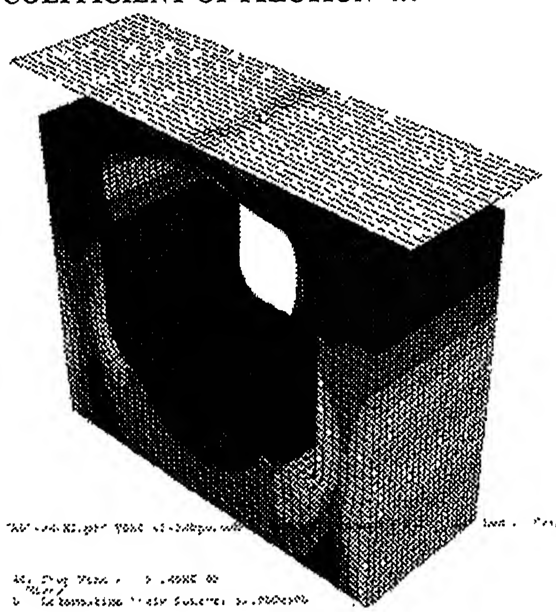
MATERIAL=EPDM, SEAL GAP (G)=4, WIDTH (W) = 23.5, VERTICAL HEIGHT (VL) = 18, SIDE LENGTH (S) =1
INNER PRESSURE (P) = 23 kPa
CONTACT PRESSURE=0kPa
MAXIMUM STRESS=........
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.6



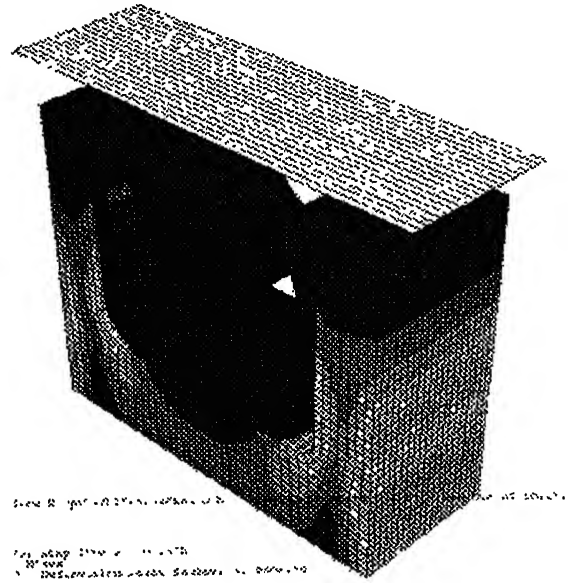
MATERIAL=FKM, SEAL GAP (G)=4, WIDTH (W) = 23.5, VERTICAL HEIGHT (VL) = 18, SIDE LENGTH (S) =1
INNER PRESSURE (P) = 23 kPa
CONTACT PRESSURE=.....
MAXIMUM STRESS=........
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.6



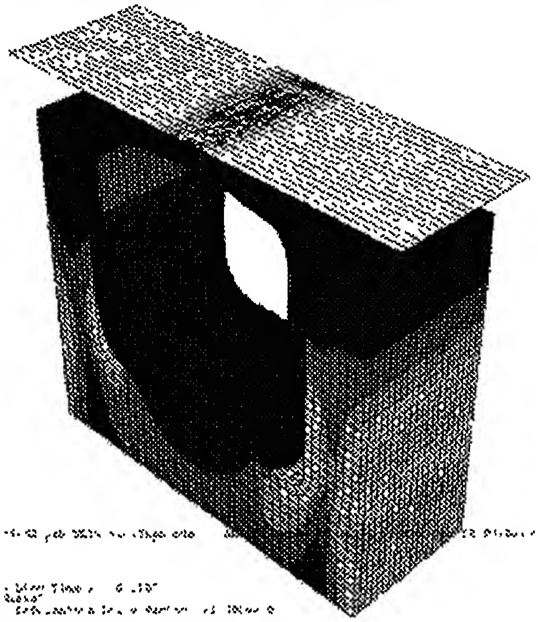
MATERIAL=EPDM, SEAL GAP (G)=4, WIDTH (W) = 23.5, VERTICAL HEIGHT (VL) = 18, SIDE LENGTH (S) =1
INNER PRESSURE (P) = 30 kPa
CONTACT PRESSURE=54kPa
MAXIMUM STRESS=1.8MPa
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.6



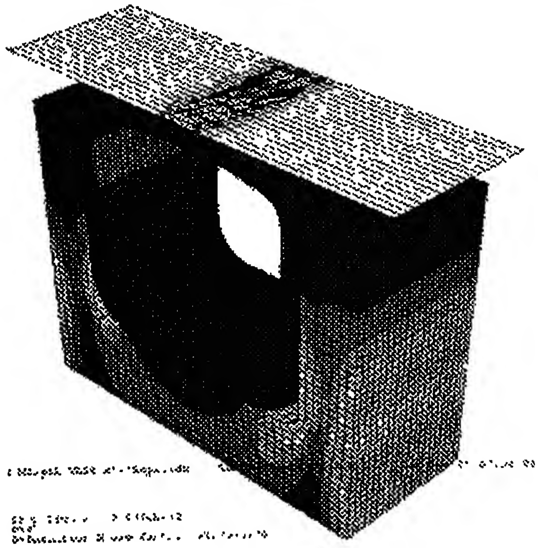
MATERIAL=FKM, SEAL GAP (G)=4, WIDTH (W) = 23.5, VERTICAL HEIGHT (VL) = 18, SIDE LENGTH (S) =1
INNER PRESSURE (P) = 30 kPa
CONTACT PRESSURE=.....
MAXIMUM STRESS=........
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.6



MATERIAL=FKM, SEAL GAP (G)=4, WIDTH (W) = 23.5, VERTICAL HEIGHT (VL) =18, SIDE LENGTH (S) =1
INNER PRESSURE (P) = 40 kPa
CONTACT PRESSURE = 89.2 kPa
MAXIMUM STRESS = 2.3 MPa
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.6



MATERIAL=FKM, SEAL GAP (G)=4, WIDTH (W) = 23.5, VERTICAL HEIGHT (VL) = 18, SIDE LENGTH (S) =1
INNER PRESSURE (P) = 45 kPa
CONTACT PRESSURE = 103.6 kPa
MAXIMUM STRESS = 2.4 MPa
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.6



CHAPTER 4

FINITE ELEMENT ANALYSIS OF BEADED SEAL

4.1: ANALYSIS OF SEAL UNDER STATIC CONDITION

The same procedure adopted for unbeaded seal is also used here,

4.1.1: Parameters under study

The terminology used for beaded seal is shown in Figure 4.1.

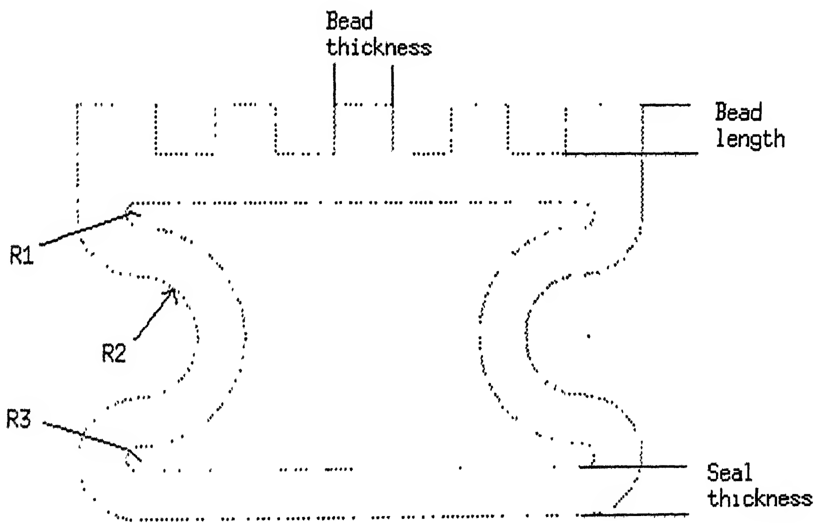


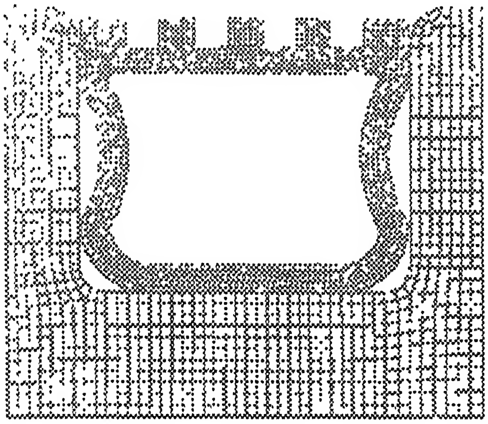
Figure 4.1: Geometry of beaded seal

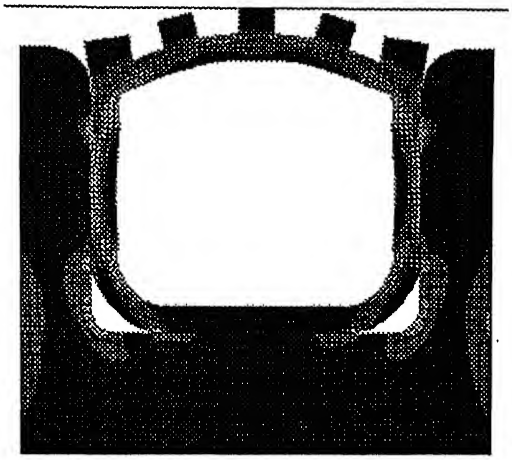
In the analysis of beaded seal many parameters are varied inorder to find the suitable dimensions of seal to withstand the specified pressure. These are given below.

- Two types of polymer are used. These are EPDM and FKM.
- Thickness of seal is varied from 1.0 to 3.0 mm insteps of 0.2 mm
- Vertical gap between seal surface and top cover is varied from 3 to 4 mm insteps of 1.0 mm
- Side gap between the seal and the seal groove is varied from zero to 1.0 mm on both the sides insteps of 0.2 mm.
- Side length of seal is varied from 1.0 to 5 mm insteps of 1mm
- Beaded width is varied from 0.5 to 4 insteps of 0.5
- Beaded height is varied from 0.5 to 4 insteps of 0.5
- Radiuses (R1, R2, R3) are varied from 0.5 to 5 insteps of 0.5
- Inflation pressure varies from 10 to 70 kPa
- Coefficient of friction varies from 0.1 to .9

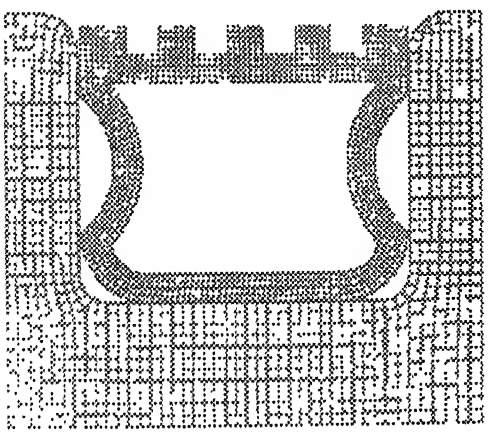
Few representative figures obtained under static condition from finite element analysis are shown in the next section

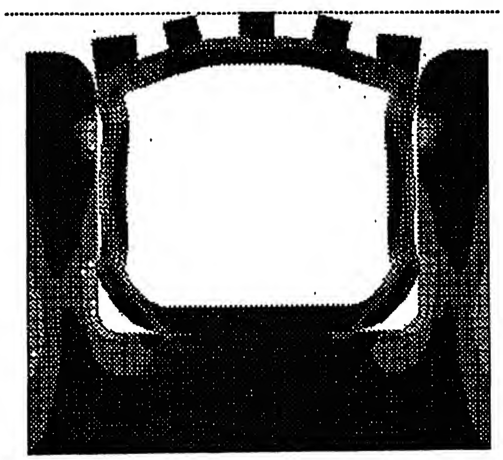
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 112.1 kPa
MAXIMUM STRESS= 1.96 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50^{o}C
COEFFICIENT OF FRICTION=0.2



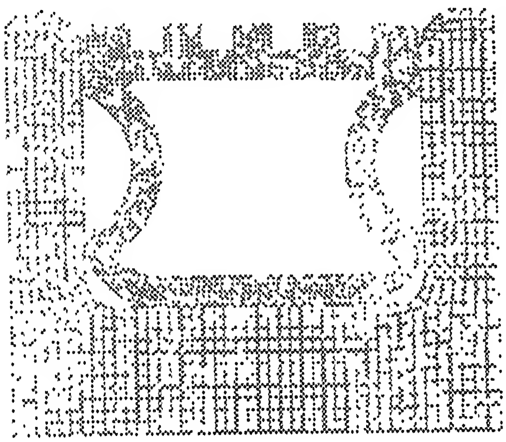


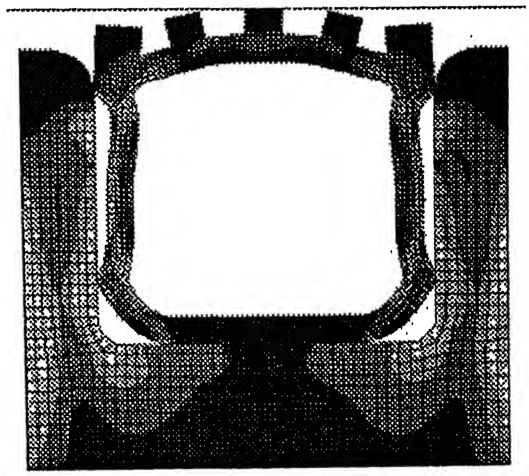
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 151.9 kPa
MAXIMUM STRESS= 2.32 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50^{o}C
COEFFICIENT OF FRICTION=0.2



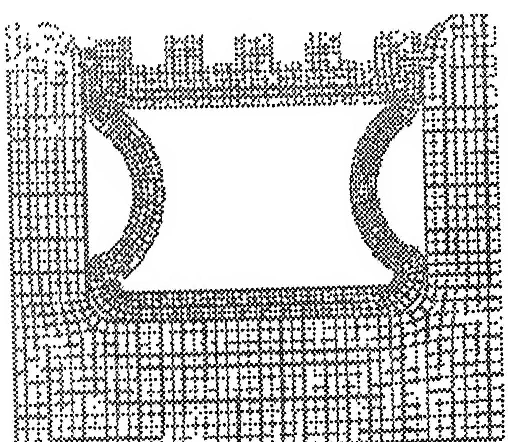


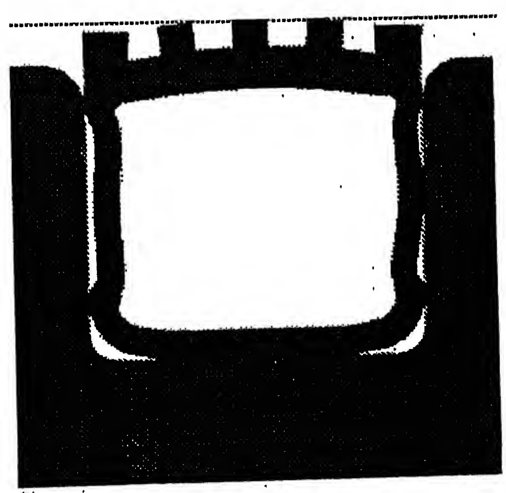
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 155.2 kPa
MAXIMUM STRESS= 1.91 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50^{O}C
COEFFICIENT OF FRICTION=0.2



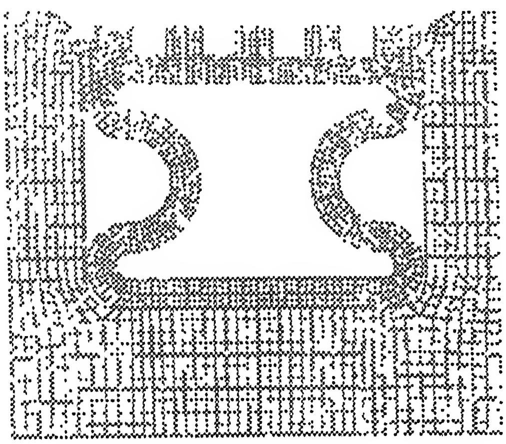


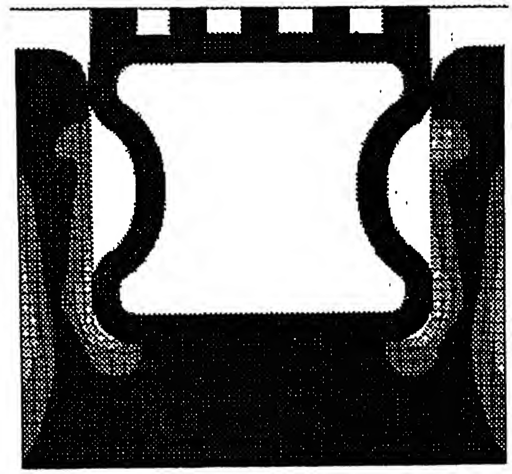
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 97.5 kPa
MAXIMUM STRESS= 3.01 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50^{O}C
COEFFICIENT OF FRICTION=0.2



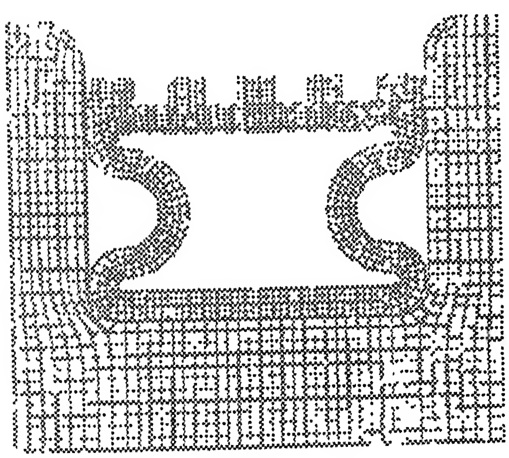


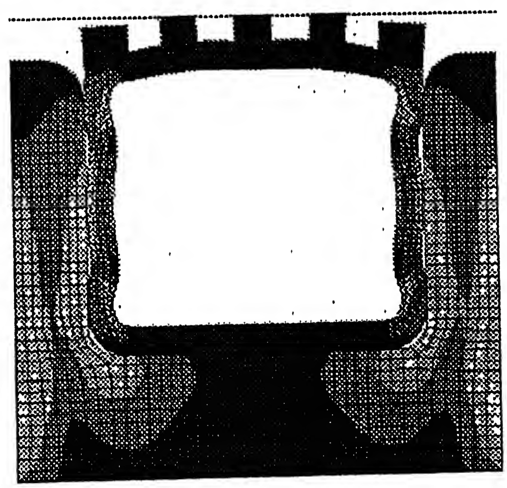
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 85.4 kPa
MAXIMUM STRESS= 0.9 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



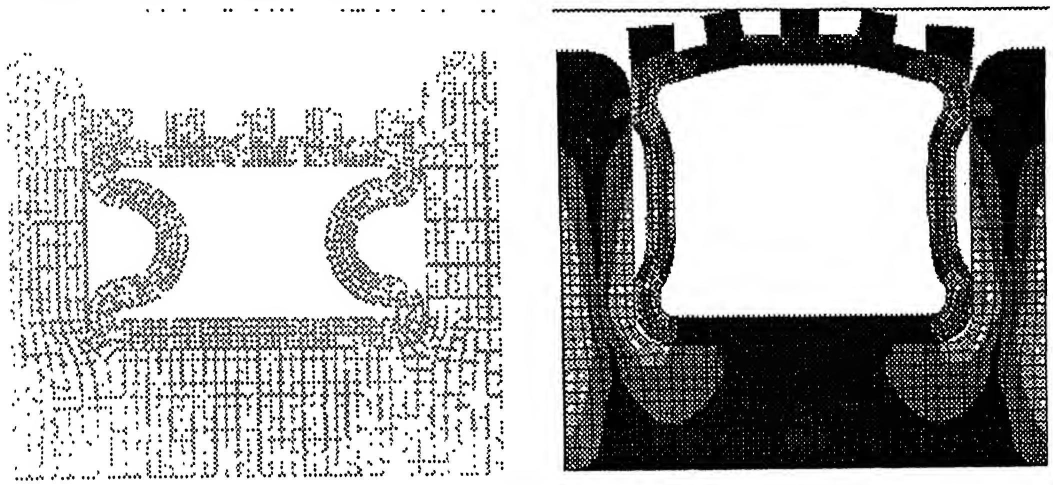


MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 100 kPa
CONTACT PRESSURE= 251.4 kPa
MAXIMUM STRESS= 2.85 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2

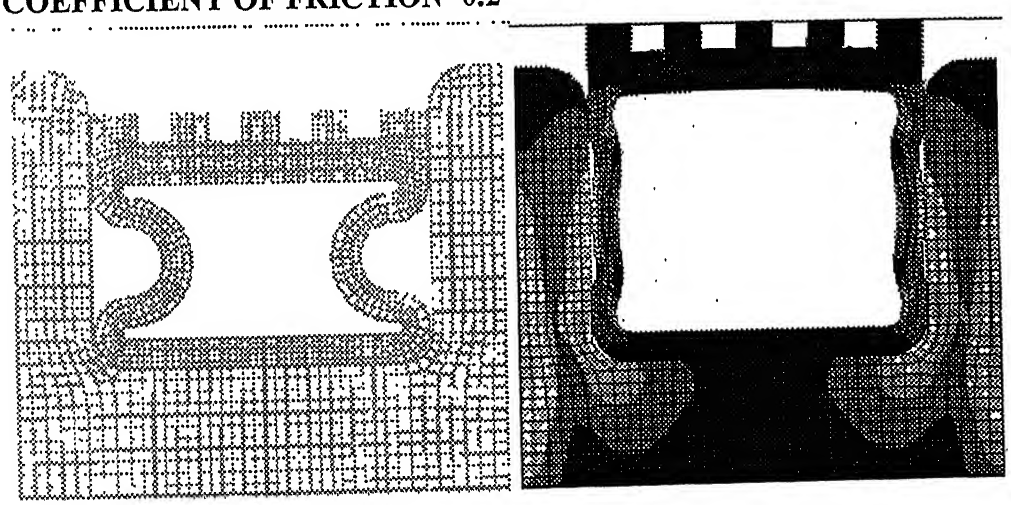




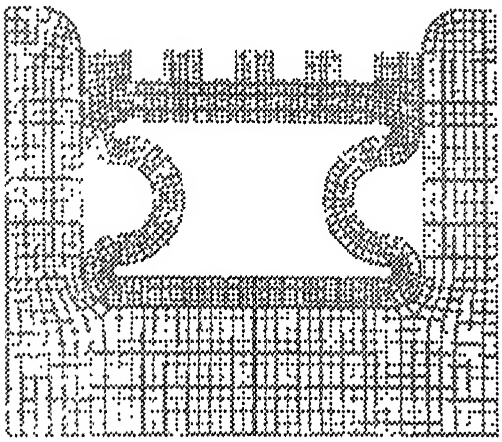
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 171.1 kPa
MAXIMUM STRESS= 2.47 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50^{O}C
COEFFICIENT OF FRICTION=0.2

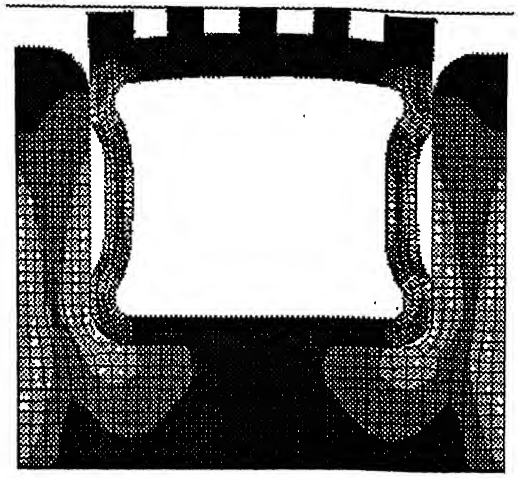


MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 100 kPa
CONTACT PRESSURE= 65.4 kPa
MAXIMUM STRESS= 2.90 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50^{O}C
COEFFICIENT OF FRICTION=0.2

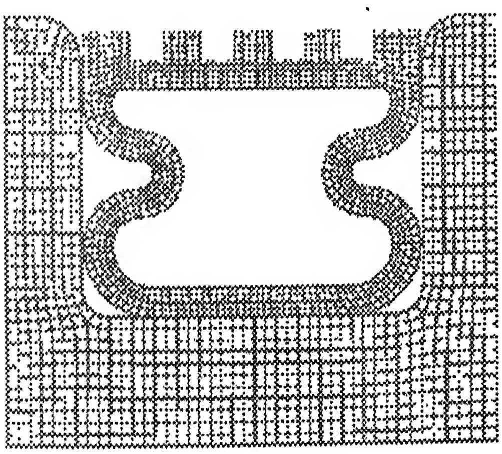


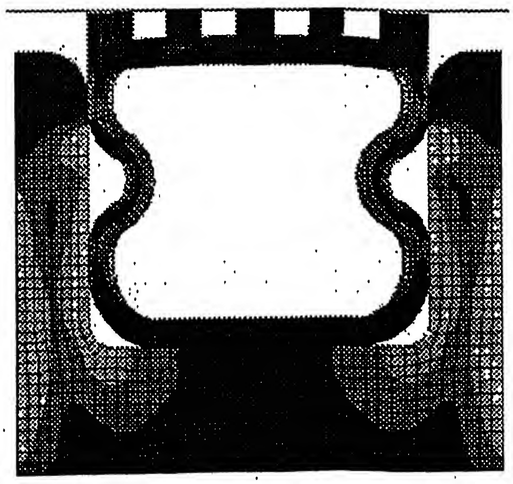
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 179.4 kPa
MAXIMUM STRESS= 2.38 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50^{O}C
COEFFICIENT OF FRICTION=0.2



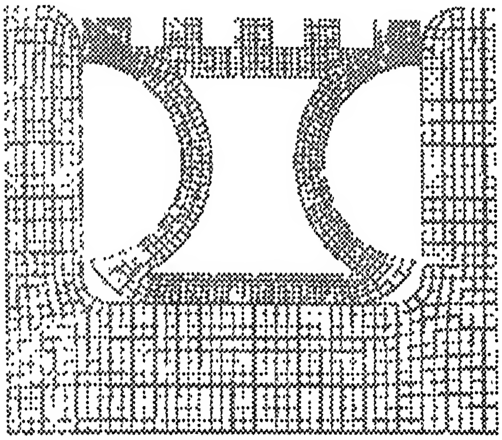


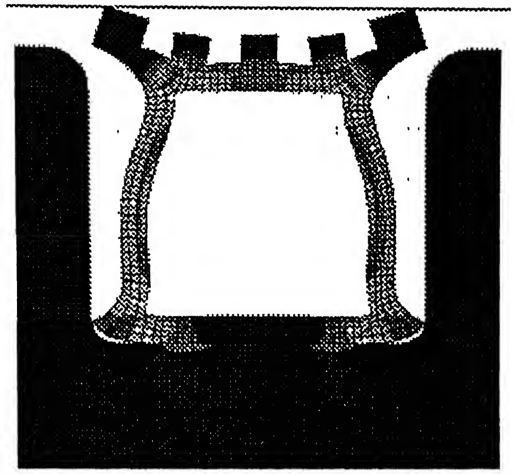
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 138.6 kPa
MAXIMUM STRESS= 0.94 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50^{O}C
COEFFICIENT OF FRICTION=0.2



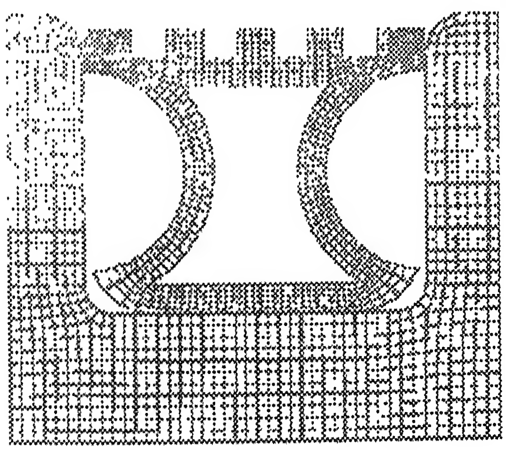


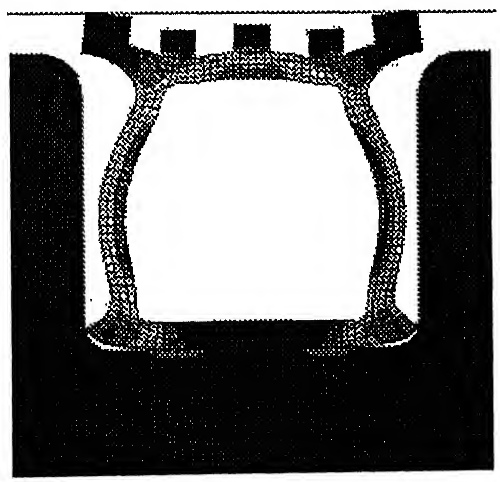
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 50 kPa
CONTACT PRESSURE=121.3kPa
MAXIMUM STRESS= 1.38 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50^{O}C
COEFFICIENT OF FRICTION=0.2



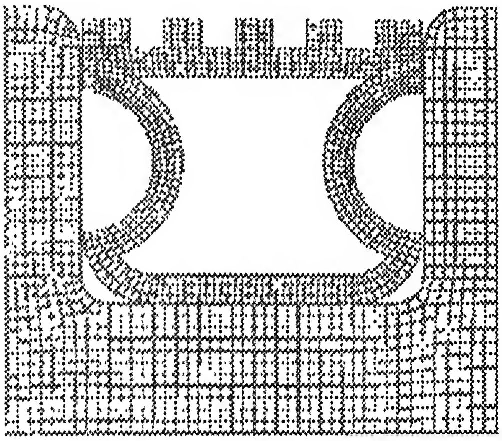


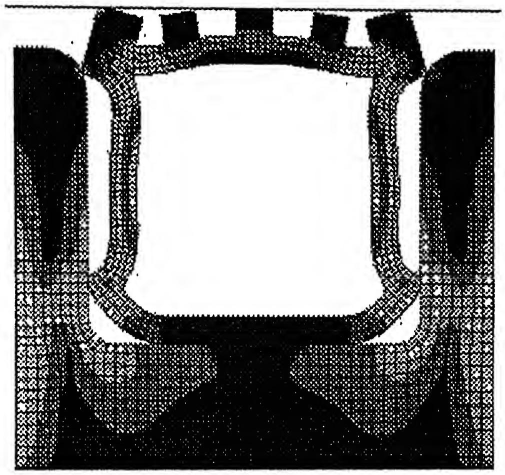
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 121.3 kPa
MAXIMUM STRESS= 2.45 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50^{O}C
COEFFICIENT OF FRICTION=0.2



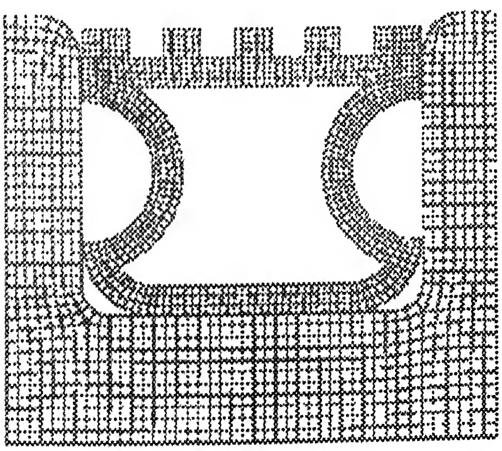


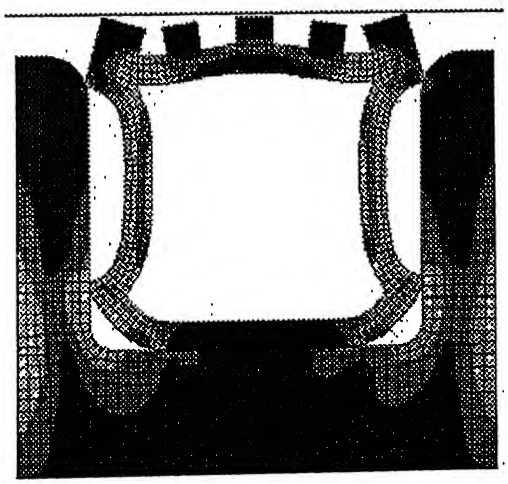
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 50 kPa
CONTACT PRESSURE= 77.2 kPa
MAXIMUM STRESS= 1.08 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50^{o}C
COEFFICIENT OF FRICTION=0.2



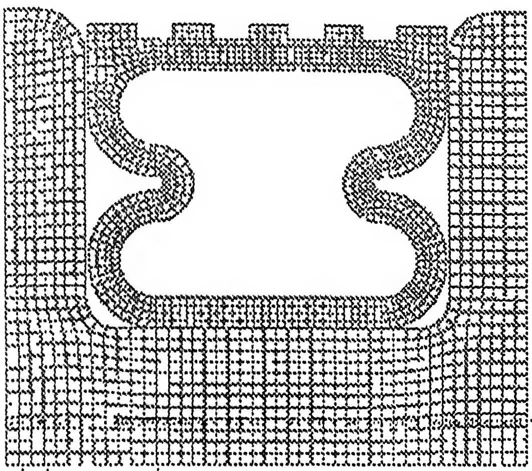


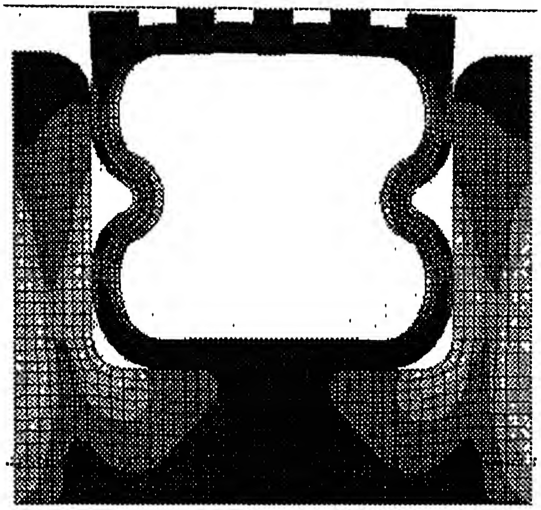
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 50 kPa
CONTACT PRESSURE= kPa
MAXIMUM STRESS= 0.75 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50^{o}C
COEFFICIENT OF FRICTION=0.2



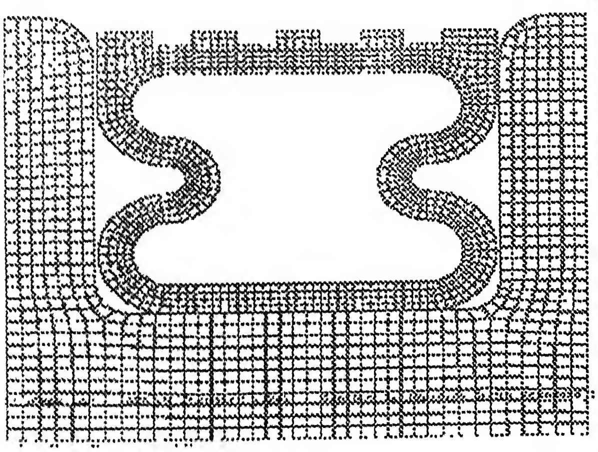


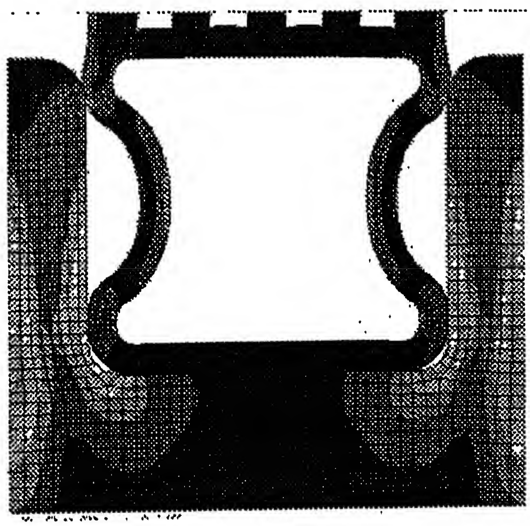
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 39.8 kPa
MAXIMUM STRESS= 0.91 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50^{O}C
COEFFICIENT OF FRICTION=0.2



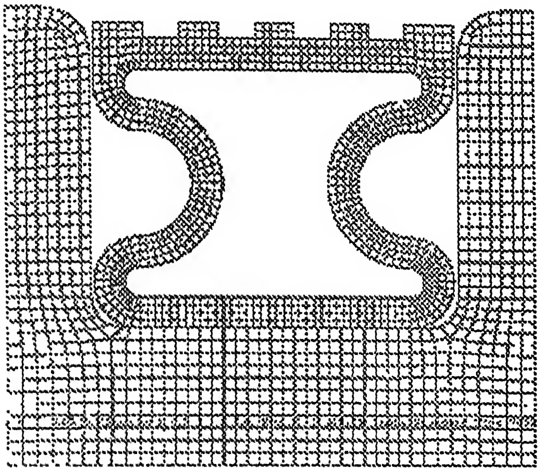


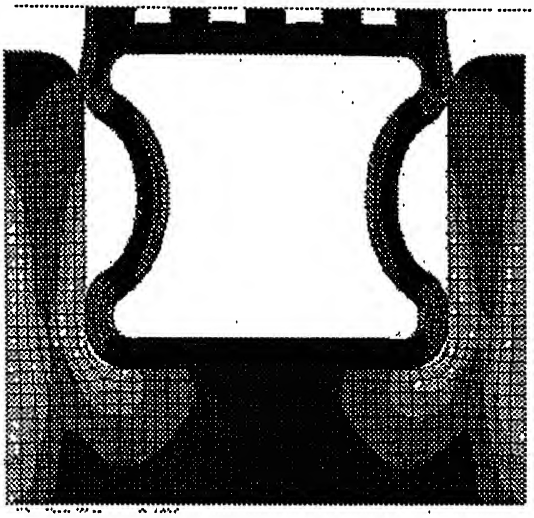
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 139.7 kPa
MAXIMUM STRESS= 0.54 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50^{O}C
COEFFICIENT OF FRICTION=0.2



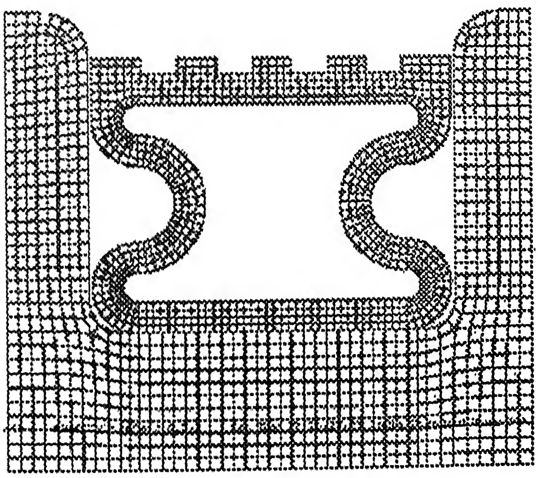


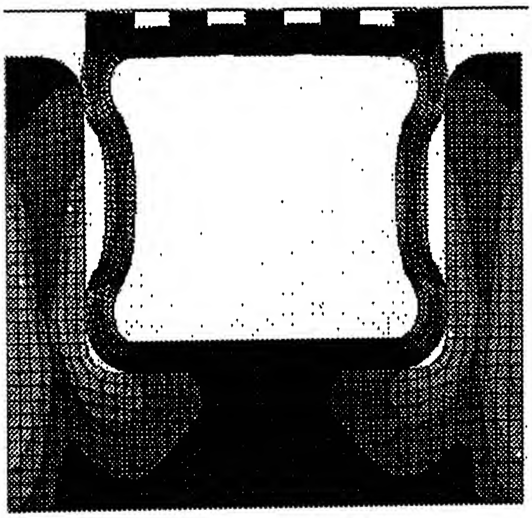
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 139.7 kPa
MAXIMUM STRESS= 0.54 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50^{o}C
COEFFICIENT OF FRICTION=0.2



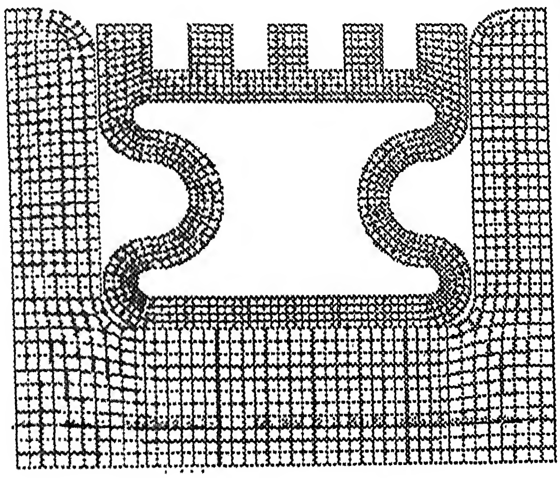


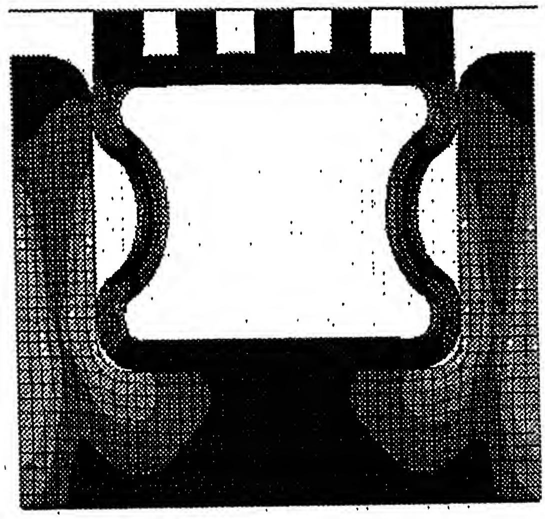
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 149.8 kPa
MAXIMUM STRESS= 1.41 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50^{o}C
COEFFICIENT OF FRICTION=0.2



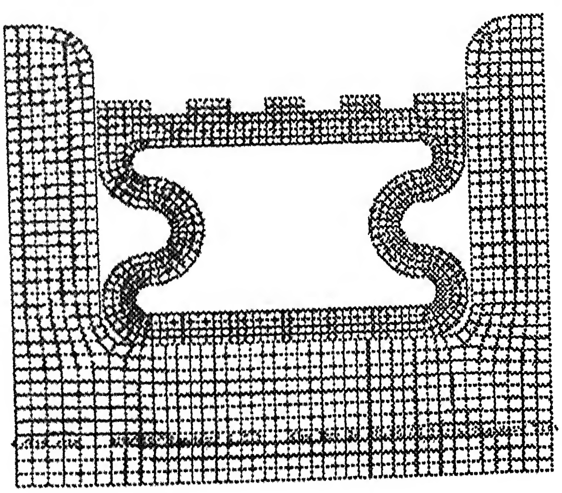


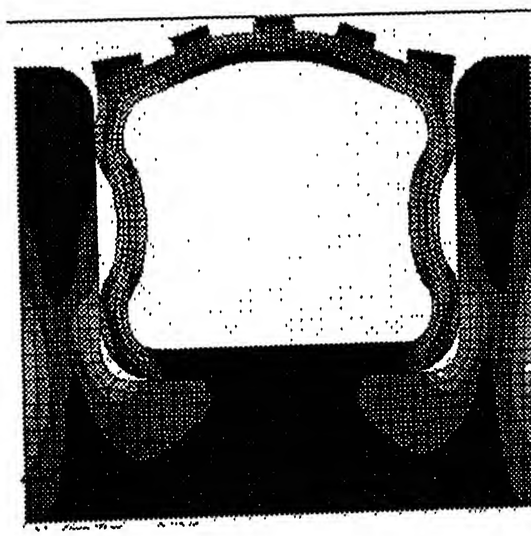
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 139.0 kPa
MAXIMUM STRESS= 1.00 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



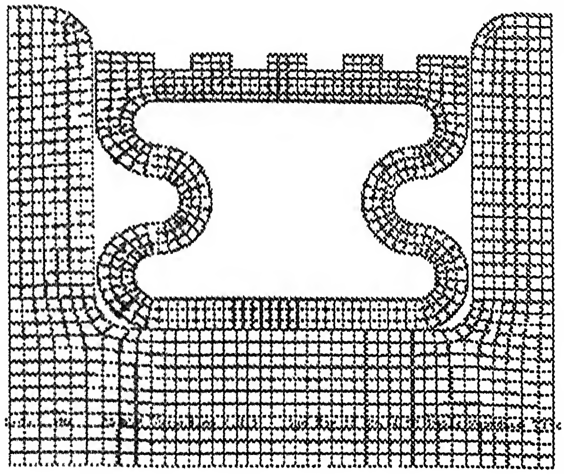


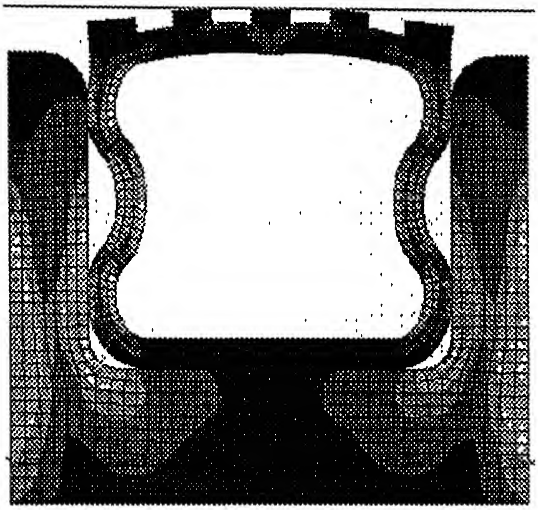
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 73.2 kPa
MAXIMUM STRESS= 1.96 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



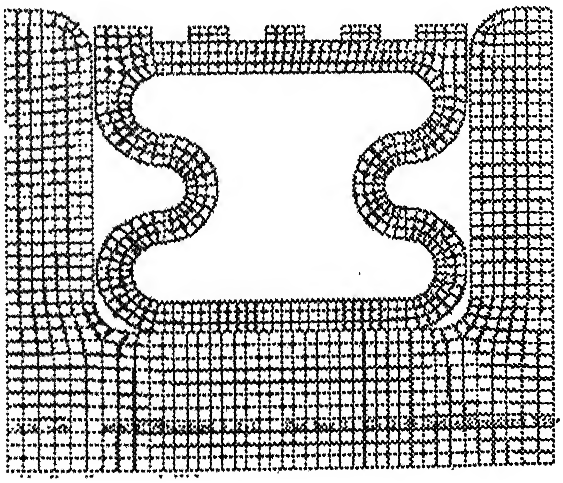


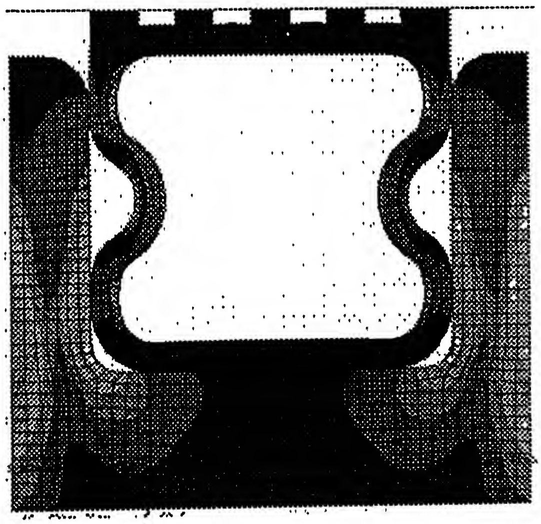
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 125.1 kPa
MAXIMUM STRESS= 0.79 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



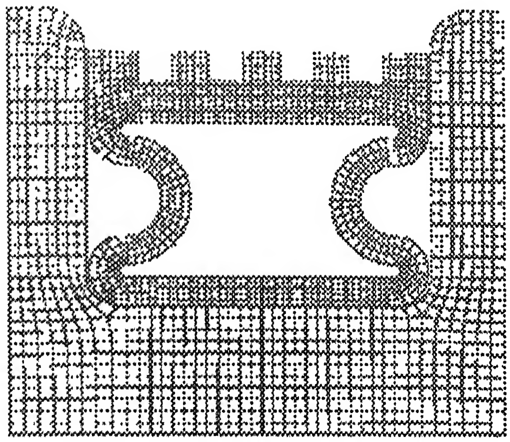


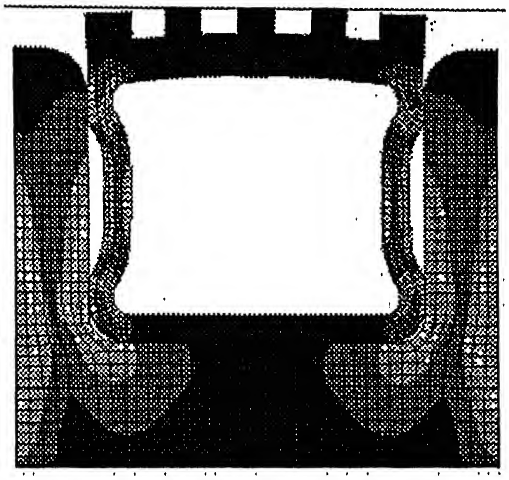
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 165.3 kPa
MAXIMUM STRESS= 1.21 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.2



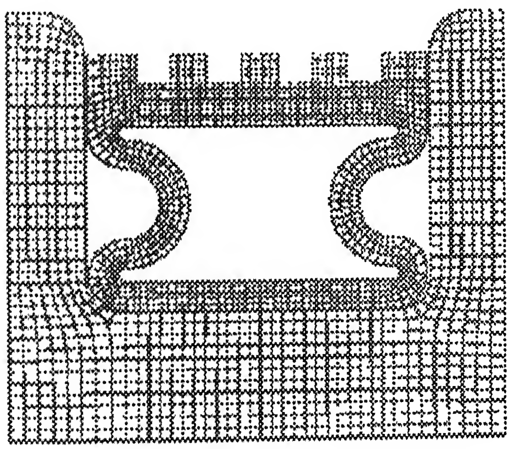


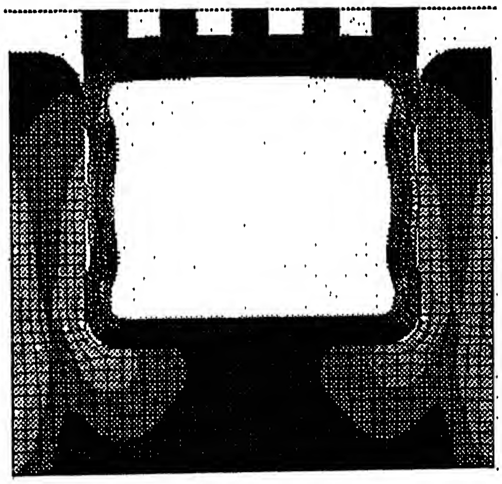
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 179.4 kPa
MAXIMUM STRESS= 2.4 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50^{o}C
COEFFICIENT OF FRICTION=0.2



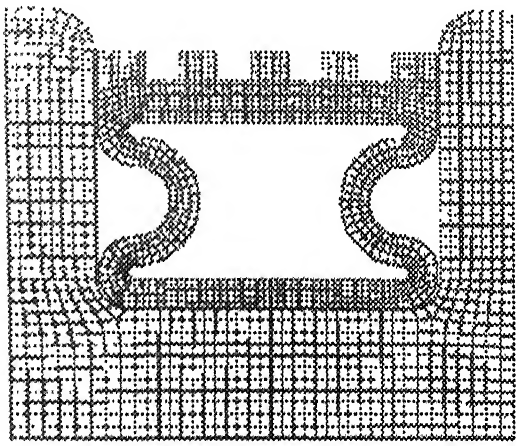


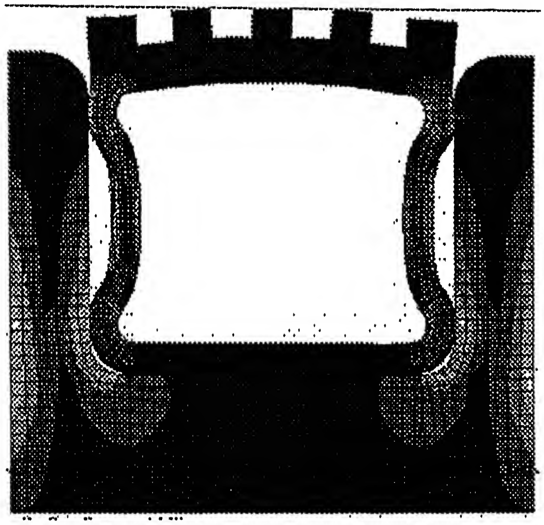
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 100 kPa
CONTACT PRESSURE= 65.4 kPa
MAXIMUM STRESS= 2.9 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50^{o}C
COEFFICIENT OF FRICTION=0.2



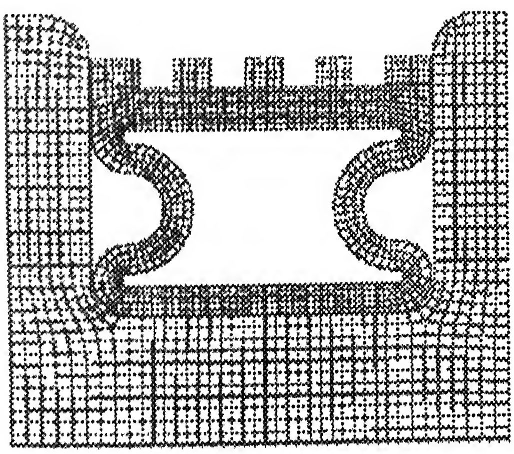


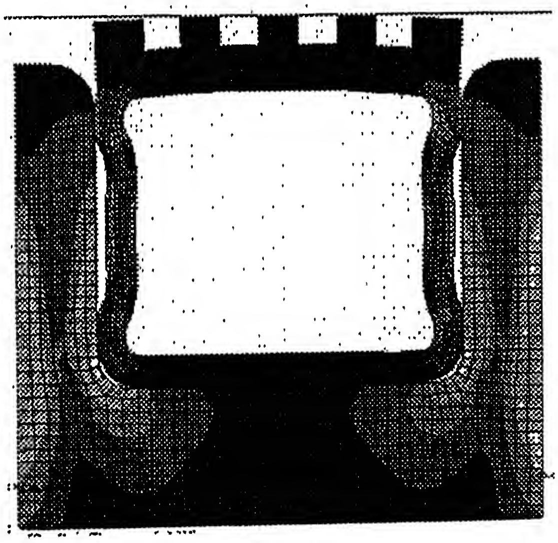
MATERIAL=FKM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 181 kPa
MAXIMUM STRESS= 1.7 MPa
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50^{o}C
COEFFICIENT OF FRICTION=0.2



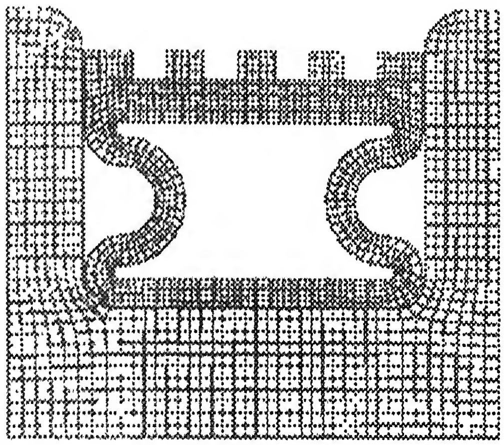


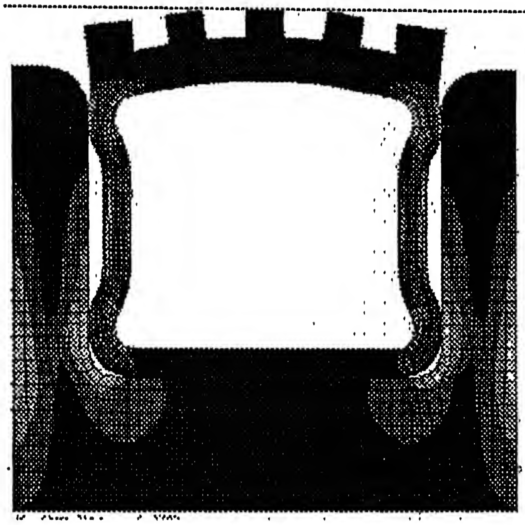
MATERIAL=FKM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 100 kPa
CONTACT PRESSURE= 258.7 kPa
MAXIMUM STRESS= 2.1 MPa
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50^{o}C
COEFFICIENT OF FRICTION=0.2



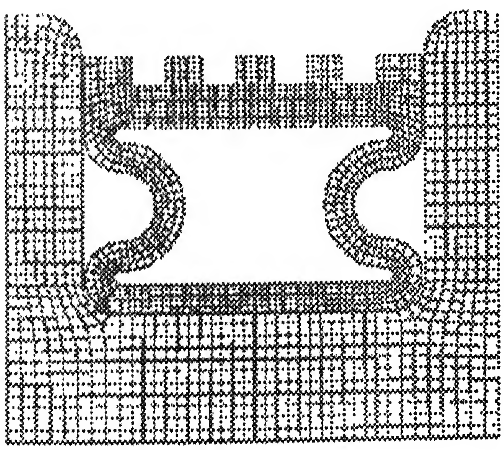


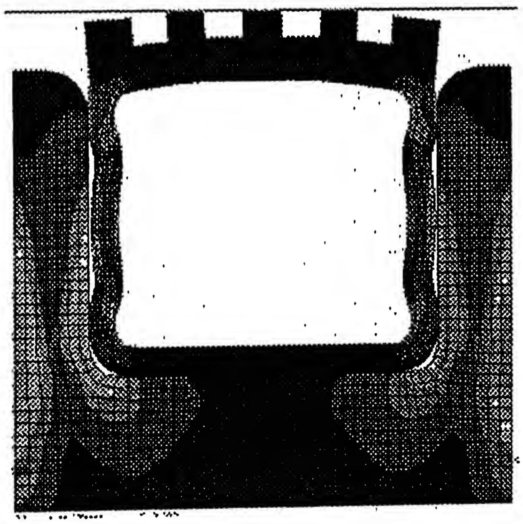
MATERIAL=EPDM, SEAL GAP (G)=4,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 139 kPa
MAXIMUM STRESS= 1.75 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50^{O}C
COEFFICIENT OF FRICTION=0.2



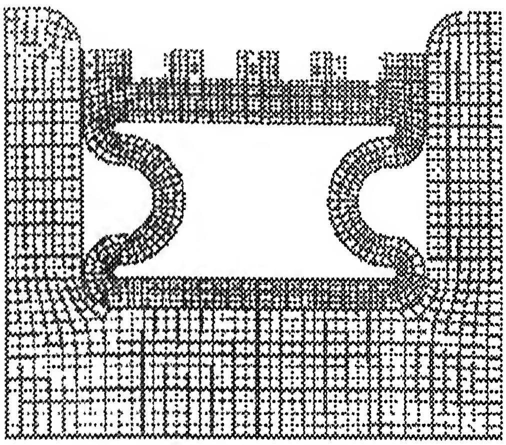


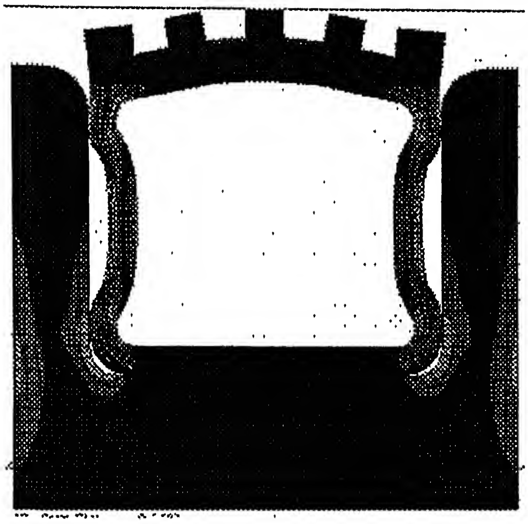
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 100 kPa
CONTACT PRESSURE= 258.8 kPa
MAXIMUM STRESS= 2.15 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50^{O}C
COEFFICIENT OF FRICTION=0.2



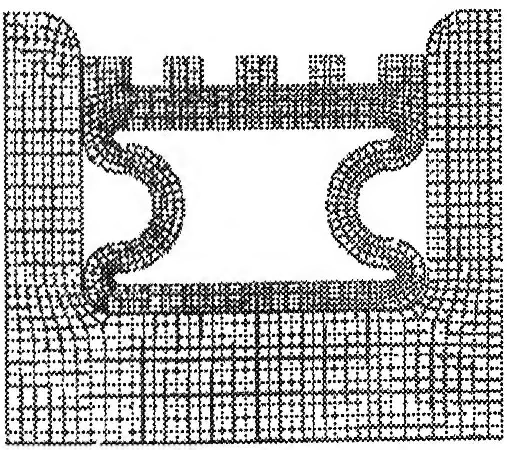


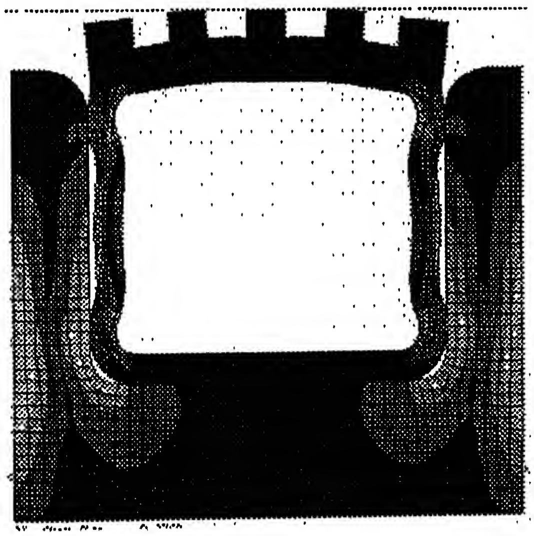
MATERIAL=FKM, SEAL GAP (G)=4,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 63.2 kPa
MAXIMUM STRESS= 1.91 MPa
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50^{o}C
COEFFICIENT OF FRICTION=0.2





MATERIAL=FKM, SEAL GAP (G)=4,
INNER PRESSURE (P) = 100 kPa
CONTACT PRESSURE= 288.5 kPa
MAXIMUM STRESS= 2.49 MPa
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50^{o}C
COEFFICIENT OF FRICTION=0.2





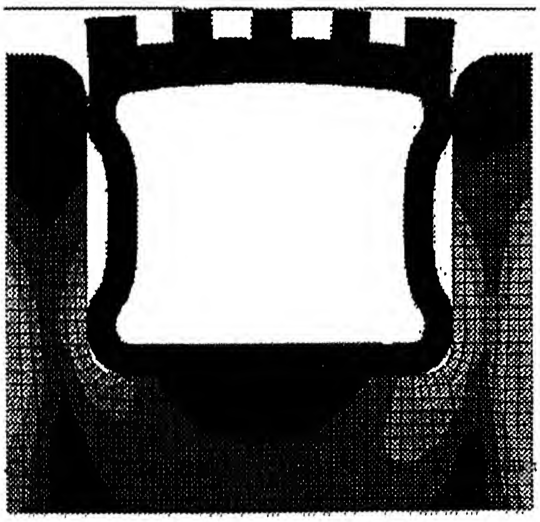
4.2: ANALYSIS OF BEADED SEAL UNDER DYANAMIC CONDITION

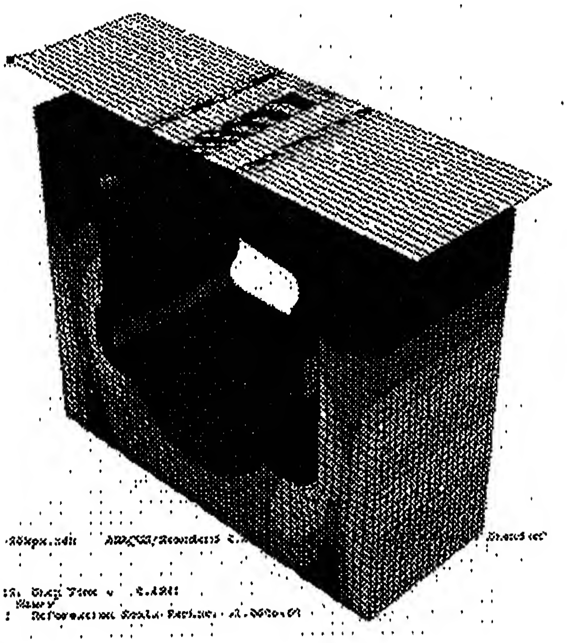
The same procedure adopted for unbeaded seal is also used here.

The seal dimensions used under these investigations are optimum dimension obtained under static condition. Here, the variable parameter is inflation pressure.

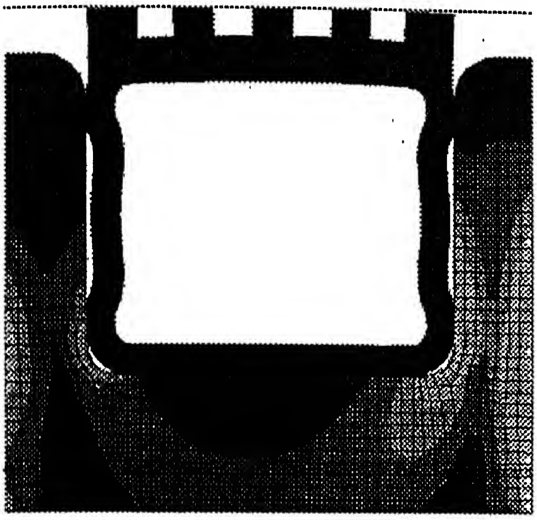
Few representative figures obtained under dynamic condition from finite element analysis are shown in the next section.

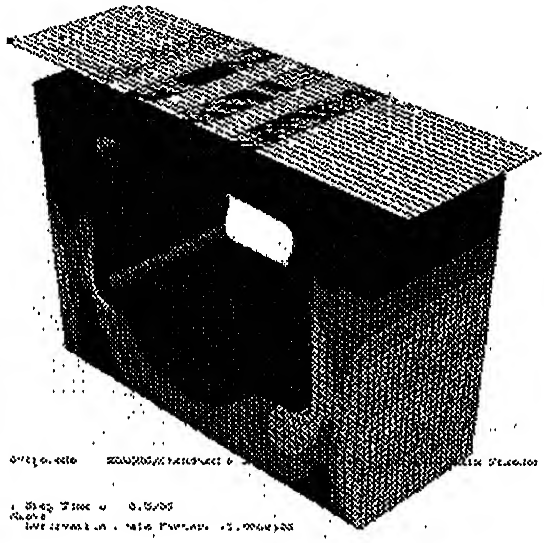
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 163.7 kPa
MAXIMUM STRESS= 1.4 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.6



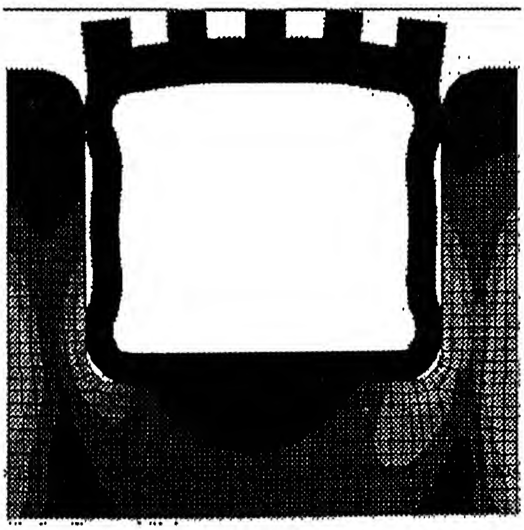


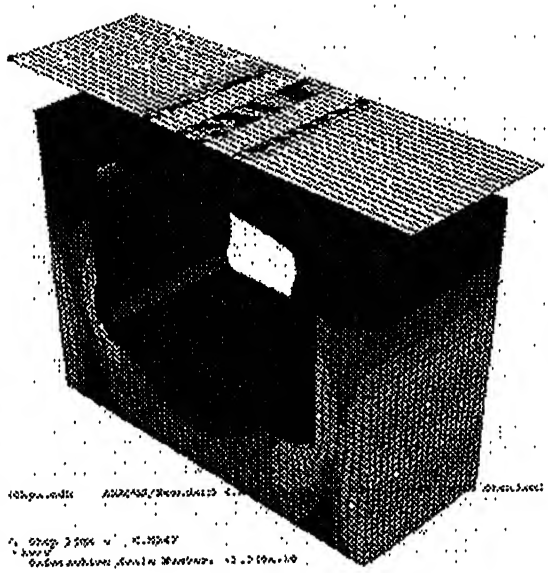
MATERIAL=EPDM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 100 kPa
CONTACT PRESSURE= 225.2 kPa
MAXIMUM STRESS= 1.8 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.6



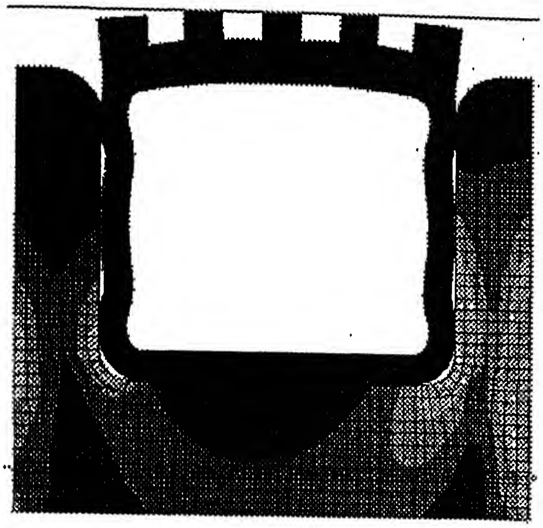


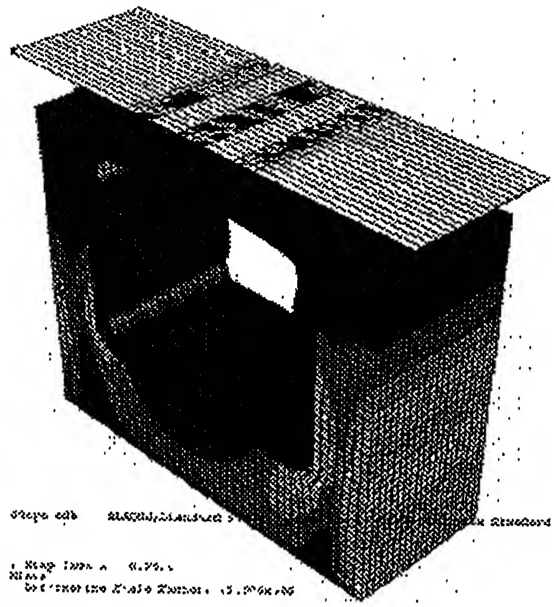
MATERIAL=EPDM, SEAL GAP (G)=4,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 241 kPa
MAXIMUM STRESS= 2.04 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.6



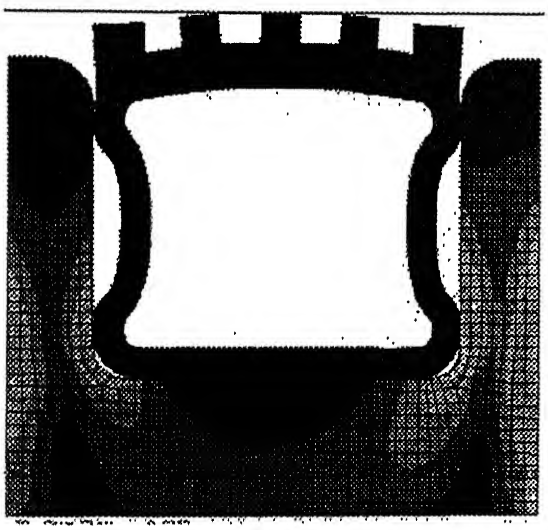


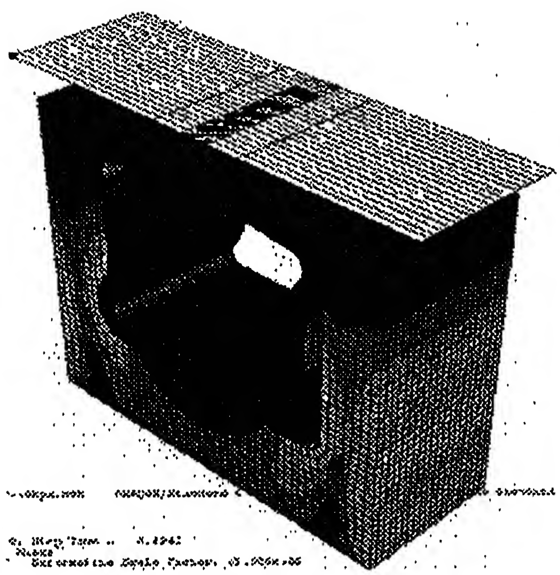
MATERIAL=EPDM, SEAL GAP (G)=4,
INNER PRESSURE (P) = 100 kPa
CONTACT PRESSURE= 296.5 kPa
MAXIMUM STRESS= 2.3 MPa
ALOWABLE STRESS=4.5 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.6



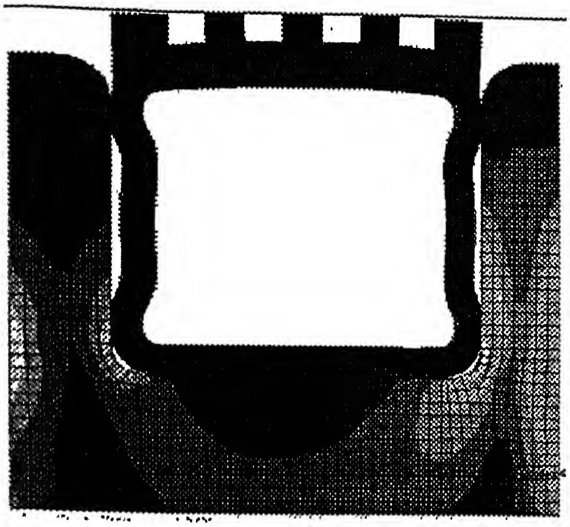


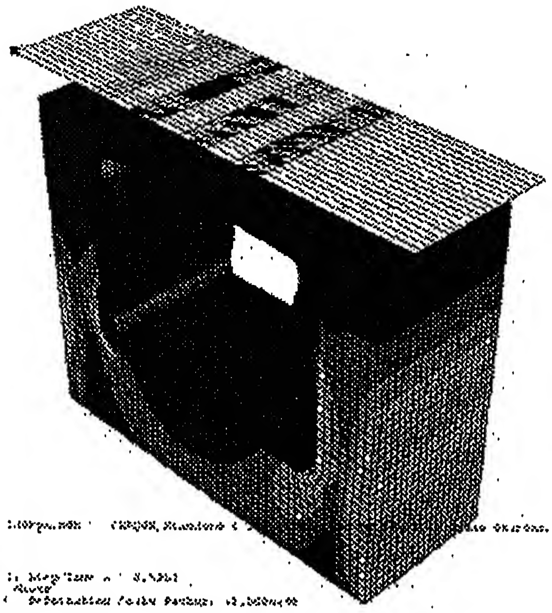
MATERIAL=FKM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 145.3 kPa
MAXIMUM STRESS= 1.62 MPa
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.6



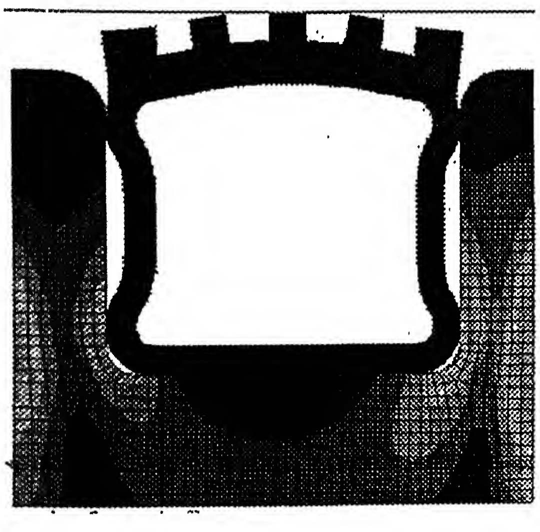


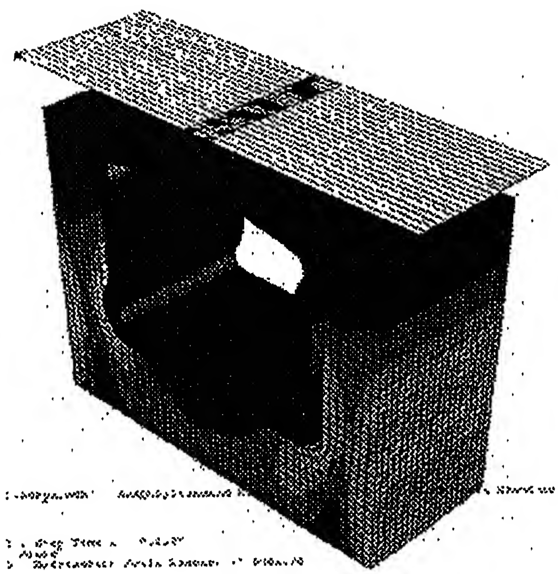
MATERIAL=FKM, SEAL GAP (G)=3,
INNER PRESSURE (P) = 100 kPa
CONTACT PRESSURE= 264.3 kPa
MAXIMUM STRESS= 2.17 MPa
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.6



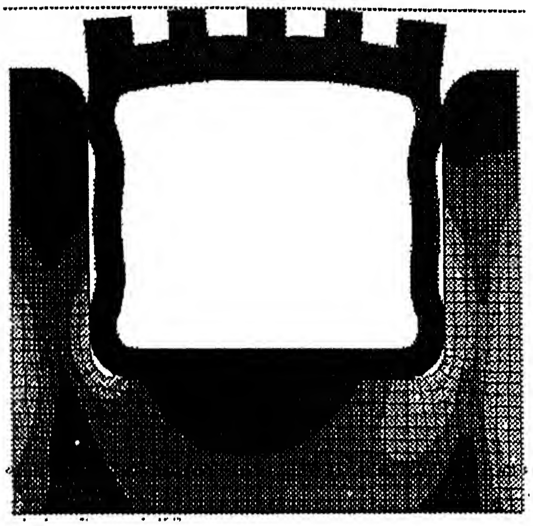


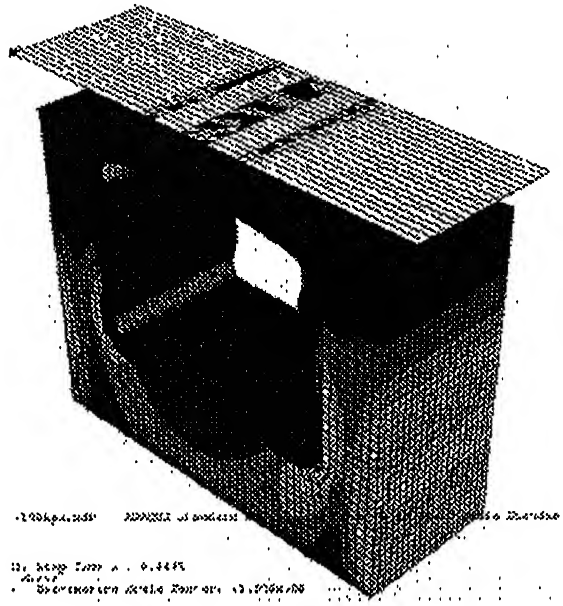
MATERIAL=FKM, SEAL GAP (G)=4,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 137.8 kPa
MAXIMUM STRESS= 2.04 MPa
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.6





MATERIAL=FKM, SEAL GAP (G)=4,
INNER PRESSURE (P) = 60 kPa
CONTACT PRESSURE= 137.8 kPa
MAXIMUM STRESS= 2.04 MPa
ALOWABLE STRESS=3.25 MPa
TEMPERATURE=50°C
COEFFICIENT OF FRICTION=0.6





CHAPTER 5

CONCLUSIONS

The major consideration for designing of polymeric seal is to provide constant sealing force at minimum inflation pressure and minimum wear at the contact surfaces under dynamic condition. An axisymmetric model of the seal is used to optimize the dimension of seal. The upper surface is the fixed rigid surface. Another part, groove made of steel, with a Young's modulus of 209 GPa and a Poisson's ratio of 0.3, is fixed with the rotatable platform, and the polymeric seal is made of incompressible polymeric material like EPDM and FKM. CAX4H elements are used to model the polymeric seal and CAX4 elements are used to steel groove. The contact pair approach is used to model the contact between the upper surface and seal surface and between the groove surface and seal surface. The mechanical interaction between the contact surfaces is assumed to be frictional contact and value is taken 0.2. Fixed boundary conditions are applied initially to the upper surface and bottom surface of groove. The inner surface of seal is loaded by the air pressure, by which inflation occur. One nonlinear static step, which includes large-displacement effects, is used to simulate these loading conditions. The following conclusions are made from the present investigation.

- The uniaxial stress strain data is fitted with various strain energy density function like Arruda-Boyce, Mooney-Rivlin, Neo-Hooken, Ogden, Polynomial, Reduced polynomial, Van der Waals and Yeoh models. The Arruda-Boyce model shows the best fit.
- To obtain the material constants, the Arruda-Boyce form of the strain energy function is used to fit the uniaxial test data.
- The optimum seal dimensions both unbeaded and beaded seals are given in Tables 5.1 and 5.2

Table 5.1: Design parameters for unbeaded seal

DIMENSIONS (mm) & PRESSURE (kPa)	GEOMETRY 1 (without bead)							
	Ethylene-Propylene				Fluorocarbon			
Seal Width	23.5				23.5			
Seal Height	18				18			
Seal Wall Thickness	2				2			
Radius of Folds	4				4			
Fillet radius (SEAL)	5				5			
Side Wall Length	1				1			
Clearance	0.2				0.2			
Seal Groove Height	21				21			
Seal Groove Width	24.0				24.0			
Fillet radius (Groove) Base & height	2 3				2 3			
INFLATION PRESSURE (kPa)	GAP 3mm		GAP 4mm		GAP 3mm		GAP 4mm	
Static S/ Dynamic **D**	Maximum Contact pressure (kPa)	Max Stress (MPa)	Maximum Contact pressure (kPa)	Max Stress (MPa)	Maximum Contact pressure (kPa)	Max Stress (MPa)	Maximum Contact pressure (kPa)	Max Stress (MPa)
Minimum inflation pressure 27 kPa **(Static)**	35.4	1.88	-	-	-	-	-	-
Minimum inflation pressure 30 kPa **(Static)**	-	-	-	-	40.2	2.3	-	-
Minimum inflation pressure 23 kPa **(Static)**	-	-	69.8	1.8	-	-	-	-
Minimum inflation pressure 30 kPa **(Static)**	-	-	-	-	-	-	39.4	2.2
Maximum inflation pressure 40 kPa to get full contact **(Static)**	42.8	1.98	-	-	-	-	-	-
Maximum inflation pressure 40 kPa to get full contact **(Static)**	-	-			-	-	-	-

Maximum inflation pressure 35 kPa to get full contact **(Static)**	-	-	-	-	41.6	2.3	-	-
Maximum inflation pressure 70 kPa to get full contact **(Static)**	-	-	-	-	-	-	110	2.6
30 **Dynamic**	35.5	2.1	-	-	-	-	-	-
30 Dynamic	-	-	40.5	2.1	-	-	-	-
40 Dynamic	-	-	-	-	51.5	2.4	-	-
40 **Dynamic**	-	-	-	-	-	-	89.2	2.3
Allowable stress (MPa; i.e. half of tensile strength)	For EPDM= 4.5 MPa, For FKM=3.25 MPA							
Side length	2							

Table 5.2: Design parameters for beaded seal

DIMENSIONS (mm) & PRESSURE (kPa)	**GEOMETRY 2 (with bead)**							
	Ethylene-Propylene				Fluorocarbon			
Seal Width	23.5				23.5			
Seal Height	18				18			
Seal Wall Thickness	2 **3 on top of seal excluding beads**				2 **3 on top of seal excluding beads**			
Radius of Folds	2.5				2.5			
Fillet radius (SEAL)	2.5				2.5			
Details of beads	Height-2 5 in number				Height-2 5 in number			
Clearance	0.2				0.2			
Seal Groove Height	21				21			
Seal Groove Width	24.0				24.0			
Fillet radius (Groove) Base & height	2 3				2 3			
INFLATION PRESSURE (kPa)	GAP 3mm		GAP 4mm		GAP 3mm		GAP 4mm	
Static S/ Dynamic **D**	Contact pressure (kPa)	Max Stress (MPa)	Contact pressure (kPa)	Max Stress (MPa)	Contact pressure (kPa)	Max Stress (MPa)	Contact pressure (kPa)	Max Stress (MPa)
60 **S**	190.204	1.55229	138.95	1.74757	180.95	1.71487	63.2039	1 91296
100 **S**	228.204	1.85753	258.776	2.15427	258.742	2.12384	288.503	2.48711
60 **D**	163.73	1.43737	240.898	2.04365	145.327	1.62376	137.844	2.04103
100 **D**	225.213	1.83737	296.462	2.30257	264.723	2.16687	289.212	2.49078

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Stress strain data for Ethylene propylene diene polymer (Four specimens)

Strain (%)	Stress (MPa)	Stress (MPa)	Stress (MPa)	Stress (MPa)
1%	0.05	0.04	0.05	0.04
2%	0.13	0.11	0.17	0.12
3%	0.23	0.21	0.17	0.17
4%	0.27	0.25	0.25	0.27
5%	0.33	0.31	0.3	0.31
6%	0.37	0.35	0.34	0.36
7%	0.41	0.39	0.38	0.4
8%	0.45	0.42	0.44	0.44
9%	0.48	0.46	0.47	0.48
10%	0.52	0.49	0.5	0.51
11%	0.54	0.52	0.53	0.54
12%	0.58	0.55	0.57	0.58
13%	0.6	0.58	0.6	0.6
14%	0.64	0.61	0.62	0.63
15%	0.67	0.63	0.66	0.66
16%	0.69	0.67	0.68	0.69
17%	0.71	0.68	0.7	0.72
18%	0.74	0.71	0.73	0.74
19%	0.77	0.73	0.75	0.76
20%	0.78	0.76	0.78	0.78
21%	0.81	0.77	0.8	0.81
22%	0.82	0.8	0.82	0.83
23%	0.84	0.82	0.84	0.84
24%	0.87	0.84	0.87	0.87
25%	0.88	0.86	0.88	0.89
26%	0.91	0.87	0.9	0.9
27%	0.92	0.89	0.92	0.93
28%	0.93	0.91	0.95	0.94
29%	0.97	0.93	0.96	0.95
30%	0.98	0.95	0.98	0.99
31%	0.99	0.97	0.99	1
32%	1.02	0.98	1.02	1.01
33%	1.03	1	1.03	1.04
34%	1.05	1.01	1.06	1.06
35%	1.06	1.03	1.07	1.06
36%	1.08	1.05	1.08	1.1

37%	1.1	1.07	1.11	1.1
38%	1.12	1.08	1.12	1.14
39%	1.13	1.1	1.14	1.15
40%	1.14	1.12	1.16	1.16
41%	1.17	1.13	1.18	1.17
42%	1.18	1.15	1.19	1.2
43%	1.2	1.17	1.21	1.21
44%	1.22	1.18	1.23	1.22
45%	1.23	1.2	1.25	1.25
46%	1.25	1.22	1.26	1.26
47%	1.27	1.23	1.28	1.27
48%	1.27	1.25	1.3	1.31
49%	1.3	1.26	1.32	1.31
50%	1.31	1.27	1.34	1.33
51%	1.33	1.3	1.36	1.36
52%	1.35	1.32	1.37	1.37
53%	1.37	1.33	1.38	1.38
54%	1.38	1.35	1.41	1.4
55%	1.41	1.37	1.42	1.43
56%	1.42	1.38	1.45	1.44
57%	1.44	1.4	1.47	1.47
58%	1.46	1.41	1.48	1.49
59%	1.48	1.43	1.51	1.49
60%	1.5	1.45	1.52	1.52
61%	1.51	1.47	1.55	1.54
62%	1.54	1.5	1.58	1.56
63%	1.56	1.51	1.59	1.58
64%	1.58	1.53	1.61	1.59
65%	1.6	1.57	1.62	1.63
66%	1.62	1.58	1.65	1.65
67%	1.64	1.6	1.67	1.66
68%	1.66	1.61	1.7	1.71
69%	1.67	1.64	1.71	1.71
70%	1.69	1.66	1.74	1.73
71%	1.72	1.67	1.77	1.75
72%	1.75	1.7	1.79	1.77
73%	1.77	1.71	1.81	1.8
74%	1.79	1.74	1.84	1.82
75%	1.81	1.76	1.86	1.86

76%	1.84	1.79	1.88	1.88
77%	1.86	1.81	1.91	1.9
78%	1.88	1.84	1.94	1.92
79%	1.91	1.86	1.96	1.95
80%	1.94	1.88	1.99	1.98
81%	1.96	1.91	2.01	2
82%	1.99	1.93	2.04	2.02
83%	2.01	1.93	2 07	2.06
84%	2.05	1.99	2.1	2.08
85%	2.06	2.01	2.13	2.11
86%	2.09	2.04	2.15	2.14
87%	2.12	2.06	2.18	2.17
88%	2.15	2.08	2.21	2.2
89%	2.17	2.11	2.25	2.23
90%	2.21	2.14	2.27	2.27
91%	2.22	2.16	2.31	2.29
92%	2.25	2.19	2.34	2.32
93%	2.29	2.23	2.36	2.34
94%	2.32	2.25	2.4	2.37
95%	2.35	2.28	2.42	2.4
96%	2.37	2.31	2.46	2.44
97%	2.41	2.34	2.49	2.47
98%	2.44	2.38	2.52	2.5
99%	2.46	2.39	2.55	2.53
100%	2.5	2.43	2.6	2.57
101%	2.54	2.45	2.61	2.6
102%	2.56	2.49	2.66	2.64
103%	2.61	2.53	2.69	2.66
104%	2.64	2.55	2.73	2.7
105%	2.66	2.59	2.76	2.73
106%	2.7	2.62	2.8	2.76
107%	2.73	2.65	2.84	2.8
108%	2.76	2.68	2.86	2.84
109%	2.8	2.72	2.9	2.87
110%	2.84	2.74	2.95	2.92
111%	2.87	2.78	2.99	2.96
112%	2.9	2.82	3.01	2.99
113%	2.94	2.84	3.05	3.02
114%	2.98	2.88	3.09	3.07

115%	3	2.92	3.13	3.09
116%	3.05	2.95	3.16	3.13
117%	3.09	2.99	3.2	3.17
118%	3.12	3.03	3.24	3.22
119%	3.15	3.07	3.28	3.25
120%	3.2	3.1	3.32	3.29
121%	3.23	3.14	3.35	3.32
122%	3.27	3.17	3.39	3.37
123%	3.3	3.21	3.44	3.4
124%	3.34	3.24	3.48	3.45
125%	3.39	3.28	3.51	3.48
126%	3.43	3.32	3.55	3.52
127%	3.46	3.36	3.59	3.56
128%	3.5	3.39	3.63	3.61
129%	3.54	3.43	3.68	3.65
130%	3.58	3.47	3.71	3.69
131%	3.63	3.52	3.75	3.72
132%	3.65	3.55	3.79	3.77
133%	3.7	3.59	3.83	3.81
134%	3.74	3.63	3.88	3.85
135%	3.79	3.67	3.92	3.89
136%	3.83	3.71	3.95	3.93
137%	3.87	3.73	4	3.98
138%	3.9	3.78	4.04	4.03
139%	3.95	3.82	4.09	4.05
140%	3.99	3.86	4.14	4.11
141%	4.04	3.91	4.18	4.15
142%	4.07	3.96	4.22	4.19
143%	4.13	3.99	4.27	4.24
144%	4.17	4.03	4.3	4.28
145%	4.22	4.08	4.35	4.33
146%	4.26	4.12	4.4	4.37
147%	4.29	4.16	4.43	4.42
148%	4.34	4.2	4.48	4.46
149%	4.38	4.24	4.52	4.51
150%	4.43	4.29	4.57	4.55
151%	4.46	4.34	4.63	4.6
152%	4.52	4.38	4.67	4.64
153%	4.57	4.42	4.71	4.68

154%	4.68	4.46	4.75	4.72
155%	4.65	4.51	4.79	4.78
156%	4.69	4.55	4.83	4.83
157%	4.75	4.6	4.88	4.87
158%	4.79	4.64	4.93	4.91
159%	4.83	4.68	4.98	4.96
160%	4.87	4.72	5.02	5
161%	4.92	4.76	5.06	5.05
162%	4.97	4.81	5.12	5.11
163%	5.01	4.85	5.16	5.15
164%	5.06	4.9	5.21	5.2
165%	5.1	4.95	5.25	5.24
166%	5.16	4.99	5.31	5.29
167%	5.2	5.04	5.34	5.33
168%	5.24	5.09	5.39	5.37
169%	5.29	5.13	5.44	5.42
170%	5.32	5.17	5.48	5.47
171%	5.37	5.21	5.52	5.52
172%	5.43	5.27	5.57	5.58
173%	5.47	5.31	5.63	5.62
174%	5.52	5.36	5.67	5.68
175%	5.56	5.41	5.71	5.72
176%	5.62	5.46	5.76	5.75
177%	5.65	5.5	5.82	5.81
178%	5.71	5.55	5.86	5.86
179%	5.76	5.6	5.9	5.9
180%	5.82	5.64	5.96	5.95
181%	5.85	5.69	6.01	6
182%	5.91	5.74	6.05	6.05
183%	5.95	5.79	6.1	6.1
184%	6	5.84	6.15	6.15
185%	6.05	5.88	6.19	6.19
186%	6.09	5.93	6.24	6.24
187%	6.14	5.98	6.28	6.28
188%	6.19	6.03	6.33	6.33
189%	6.24	6.08	6.38	6.38
190%	6.28	6.11	6.43	6.43
191%	6.34	6.17	6.47	6.48
192%	6.37	6.21	6.52	6.53

193%	6.43	6.26	6.57	6.57
194%	6.47	6.31	6.61	6.62
195%	6.52	6.36	6 67	6.66
196%	6.56	6.4	6.71	6.72
197%	6.61	6.46	6.77	6.76
198%	6.66	6.5	6.81	6.82
199%	6.71	6.54	6.86	6.87
200%	6.77	6.59	6.9	6.91
201%	6.8	6.65	6.95	6.96
202%	6.86	6.69	6.99	7.01
203%	6.91	6.74	7.05	7.05
204%	6.95	6.78	7.09	7.11
205%	7	6.84	7.14	7.15
206%	7.04	6.88	7.19	7.2
207%	7.1	6.94	7.24	7.24
208%	7.14	6.97	7.28	7.3
209%	7.18	7.03	7.34	7.35
210%	7.24	7.07	7.38	7.39
211%	7.29	7.12	7.43	7.43
212%	7.34	7.17	7.47	7.49
213%	7.39	7.22	7.53	7.53
214%	7.44	7.27	7.56	7.58
215%	7.49	7.32	7.61	7.63
216%	7.54	7.36	7.65	7.67
217%	7.58	7.41	7.71	7.72
218%	7.63	7.46	7.75	7.77
219%	7.68	7.51	7.81	7.82
220%	7.73	7.55	7.84	7.87
221%	7.77	7.61	7.91	7.92
222%	7.82	7.66	7.94	7.96
223%	7.86	7.7	7.99	8
224%	7.91	7.76	8.03	8.05
225%	7.95	7.8	8.08	8.09
226%	8	7.85	8.13	8.15
227%	8.05	7.89	8.17	8.2
228%	8.09	7.94	8.22	8.24
229%	8.15	7.99	8.27	8.29
230%	8.19	8.04	8.32	8.33
231%	8.24	8.09	8.36	8.38

232%	8.29	8.14	8.4	8.42
233%	8.33	8.18	8.45	8.46
234%	8.39	8.22	8.5	8.53
235%	8.43	8.27	8.54	8.56
236%	8.48	8.32	8.58	8.61
237%	8.52	8.38	8.62	8.65
238%	8.57	8.41	8.68	8.7
239%	8.62	8.46	8.73	8.74
240%	8.67	8.5	8.77	8.8
241%	8.71	8.56	8.81	8.84
242%	8.76	8.6	8.86	8.88
243%	8.8	8.65	8.9	8.93
244%	8.84	8.69	8.95	8.97
245%	8.88	8.74	8.99	9.02
246%	8.94	8.79	9.04	9.05
247%	8.98	8.83	9.09	9.1
248%	9.02	8.88	9.13	9.14
249%	9.07	8.93	9.17	9.19
250%		8.97	9.21	9.22
251%		9.02	9.26	9.27
252%		9.07	9.31	9.32
253%		9.12	9.35	9.36
254%		9.16	9.39	9.41
255%		9.2	9.44	9.45
256%		9.24	9.47	9.49
257%		9.28	9.52	9.53
258%		9.34	9.56	9.58
259%		9.38	9.61	
260%		9.42	9.65	
261%		9.47	9.69	
262%		9.52	9.73	
263%		9.56	9.77	
264%		9.61	9.81	
265%		9.64	9.85	
266%		9.68	9.9	
267%		9.73		
268%		9.77		
269%		9.81		

VALIDITY OF ABAQUS:

To find out the validity of ABAQUS software, an example of cantilever beam with one edge fixed is taken here and shown in Figure1.

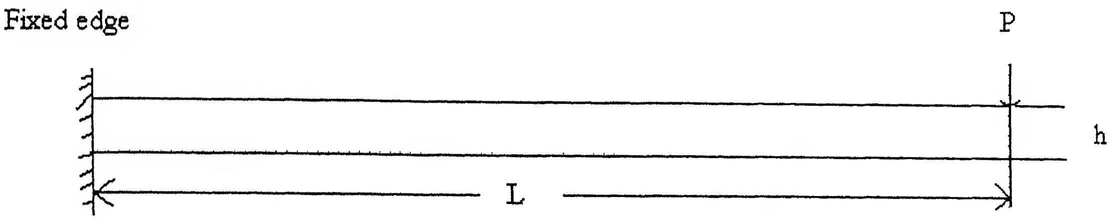

Figure1: A simple cantilever beam

Parameters: Length L = 100 m Height h = 5 m

Load P = 100 N width b = 1m

Young's modulus E = 2.09 x 10^{11} N/m^2

Exact value of deflection at the end point is $\delta_e = \dfrac{PL^3}{3EI}$

Where I is moment of inertia, $I = \dfrac{bh^3}{12}$,

After calculation $\boldsymbol{\delta_e}$**= 1.531x 10^{-5} m**

Now, the deflection at the end point is obtained through ABAQUS where the problem is divided in four steps

1) Deflection for **Step A** (Figure.2)

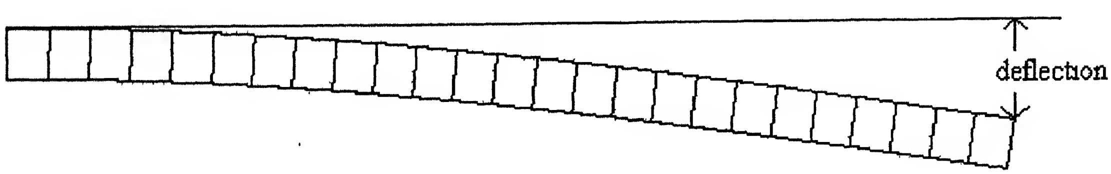

Figure 2

Deflection δ_a **= 1.141x10^{-5} m**

2) Deflection for **Step B** (Figure 3)

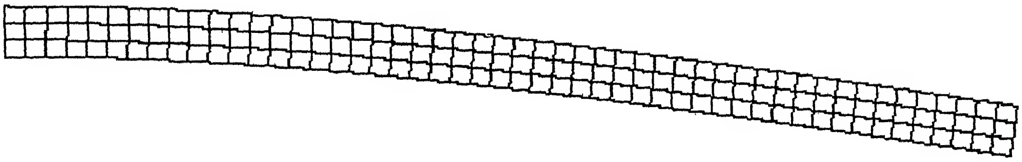

Figure 3

Deflection δ_b = **1.4291x10^{-5} m**

3) Deflection for **Step C** (Figure 4)

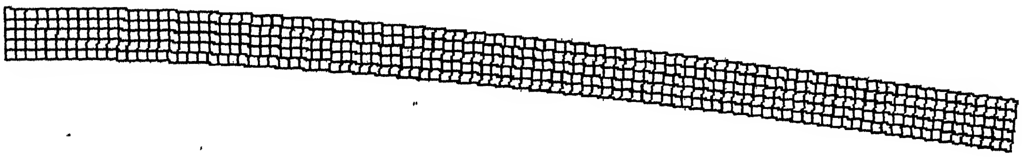

Figure 4

Deflection δ_c = **1.504x10^{-5} m**

4) Deflection for **Case D** (Figure 5)

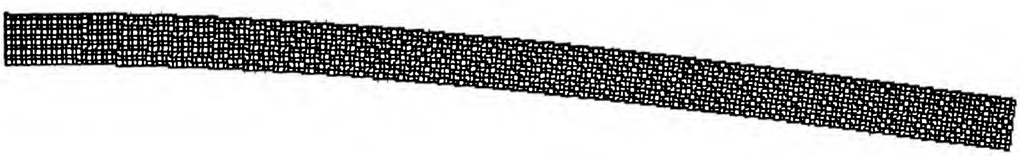

Figure 5

Deflection δ_d = **1.526x10^{-5} m**

So, when the number of element increases, the deflection approaches to the exact value obtained through numerical calculation. It shows that the analysis is in right direction.